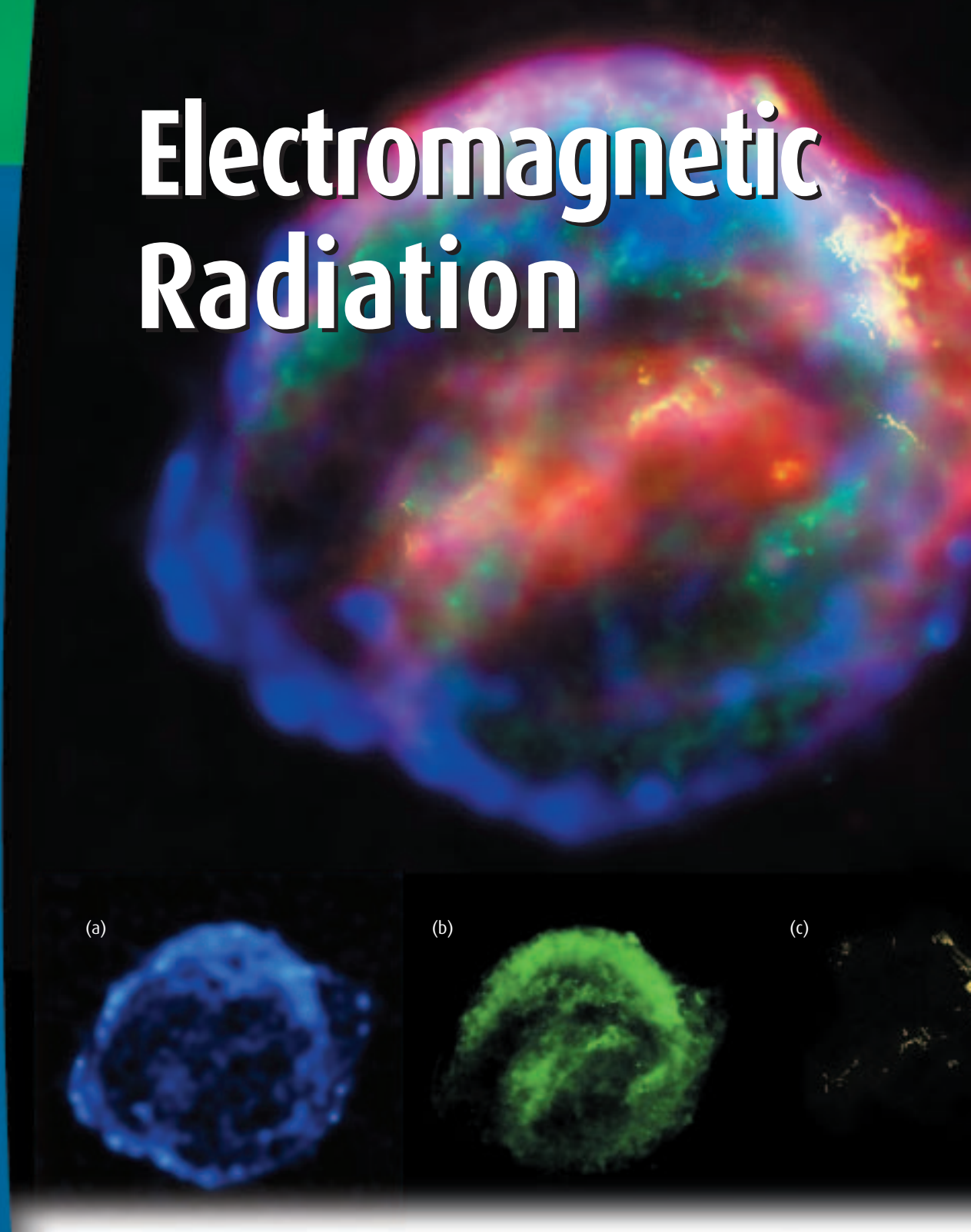
UNIT

VII

Electromagnetic Radiation



This series of photos of a supernova remnant shows the various types of electromagnetic radiation that are being emitted from the supernova remnant. The large image is a composite. Images (a) and (b) were taken by the Chandra space telescope (high-energy and low-energy X ray), image (c) was taken by the Hubble space telescope (visible part of the spectrum), and image (d) by the Spitzer space telescope (infrared).

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Unit at a Glance

CHAPTER 13 **The wave model can be used to describe the characteristics of electromagnetic radiation.**

13.1 What Is Electromagnetic Radiation?

13.2 The Speed of Electromagnetic Radiation

13.3 Reflection

13.4 Refraction

13.5 Diffraction and Interference

CHAPTER 14 **The wave-particle duality reminds us that sometimes truth really *is* stranger than fiction!**

14.1 The Birth of the Quantum

14.2 The Photoelectric Effect

14.3 The Compton Effect

14.4 Matter Waves and the Power of Symmetric Thinking

14.5 Coming to Terms with Wave-Particle Duality and the Birth of Quantum Mechanics

Unit Themes and Emphases

- Diversity and Matter
- Nature of Science
- Scientific Inquiry

Focussing Questions

The study of electromagnetic radiation and its behaviour requires interpretation of evidence to form theories and models. As you study this unit, consider these questions:

- What roles do electricity and magnetism play in electromagnetic radiation?
- Does electromagnetic radiation have a wave or a particle nature?
- What experimental evidence is required to decide whether electromagnetic radiation has a wave or a particle nature?

Unit Project

From Particle to Quantum

- When you have finished this unit you will be able to use experimental evidence concerning electromagnetic radiation to describe our current understanding of light. You will be able to craft a multi-media presentation of highlights in the development of this understanding.

CHAPTER

13

The wave model can be used to describe the characteristics of electromagnetic radiation.

Key Concepts

In this chapter, you will learn about

- speed and propagation of electromagnetic radiation
- reflection, refraction, diffraction, and interference
- total internal reflection and Snell's Law

Learning Outcomes

When you have completed this chapter, you will be able to:

Knowledge

- describe how accelerating charges produce EMR
- explain the electric and magnetic fields associated with the propagation of EMR
- explain how the speed of EMR can be investigated and calculated
- describe reflection, refraction, total internal reflection, and simple optical systems
- describe diffraction, interference, and polarization and how this supports the wave model of light

Science, Technology, and Society

- explain that scientific knowledge may lead to the development of new technologies and new technologies may lead to scientific discovery
- explain that scientific knowledge is subject to change as new evidence is found and as laws and theories are tested and subsequently restricted, revised, or reinforced based on new findings and new technologies

▲ **Figure 13.1** A Fresnel lens captures light from a lamp and redirects it into a concentrated beam. This 19th-century lens technology used many prisms to produce a light that could be seen for great distances.

When you open your eyes in the morning, the first thing you see is light. In fact, it is the only thing you see. In general, what we perceive with our eyes is a combination of many colours, each with varying brightness, but all coming together through the optical system of our eye. It is light or, more broadly speaking, a form of electromagnetic radiation (EMR), which produces an image in the human eye. But what is EMR? How is it produced? How is it transmitted and at what speed? These questions are historically significant, guiding the direction of research and debate over the ages. Finding answers has helped us understand the fundamental principles of our universe and has enabled advances in technology in areas such as lenses (Figure 13.1), fibre optics, and digital devices. Radios, lasers, global positioning systems, and compact discs (CDs) are examples of devices that depend on an understanding of EMR.

The nature of light has long been a topic of intrigue and debate. Early Greek scientific thought was based on the work of Aristotle and Euclid, who concerned themselves with the physical and geometric mechanisms of visual perception. A more modern debate ensued as detailed evidence began to be collected about the wave and/or particle nature of light. Isaac Newton (1642–1727) and Christiaan Huygens (1629–1695) defined this debate with evidence from early experiments. Newton put forward the particle or corpuscular theory, while Huygens supported the wave model. Today, both the particle and wave models of light have some validity and contribute to our present understanding, described by the quantum model of light.

In this chapter, you will see that visible light is only one form of EMR. You will also discover that the concepts of electrical charge and magnetic fields, explored in Chapters 10–12, come together when you consider EMR. You will investigate the generation, speed, and propagation of EMR, and see how light can be reflected, refracted, diffracted, and polarized. In each instance, the wave and particle nature of light is revealed, helping us to understand these complex phenomena and apply them in new technologies.

13-1 QuickLab

Investigating Light as a Form of EMR

Problem

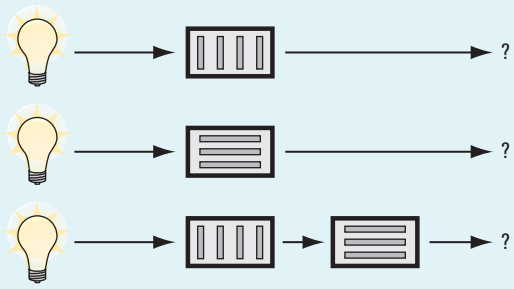
How can the properties of light be revealed?

Materials

light source
2 polarizing filters

Procedure

1. Place a light source in front of one polarizing filter and observe whether the light is able to penetrate the filter.



▲ **Figure 13.2**

2. Turn the filter 90 degrees as shown in Figure 13.2 and observe whether the light is able to penetrate the filter.
3. Place the filters at 90 degrees to one another and observe whether the light is able to penetrate the filters.
4. Slowly rotate one of the filters and observe whether the light is able to penetrate both filters at a variety of angles and positions.

Questions

1. Can visible light pass through a single polarizing filter, regardless of how it is orientated?
2. Can visible light pass through two filters when they are aligned at 90 degrees to one another?
3. Describe one characteristic of EMR indicated by your observations of light in this QuickLab.
4. Do the observations made in this investigation explain what EMR is, or do they simply reveal one characteristic of EMR?

Think About It

1. Do your observations from 13-1 QuickLab give information on whether electromagnetic radiation has wave or particle characteristics? Explain.
2. What experimental evidence would be needed to decide whether electromagnetic radiation has a wave or a particle nature?

Discuss your answers in a small group and record them for later reference. As you complete each section of this chapter, review your answers to these questions. Note any changes in your ideas.

13.1 What Is Electromagnetic Radiation?

electromagnetic radiation: radiant energy in the form of a wave produced by the acceleration of electrons or other charged particles. EMR does not require a material medium; can travel through a vacuum.

frequency: the number of cycles per unit of time

wavelength: the distance between adjacent points that vibrate in phase with one another in a wave

Electromagnetic radiation (EMR) is radiant energy, energy that travels outward in all directions from its source. There are different types of EMR, some very familiar, and others rarely mentioned outside scientific discussions. Electromagnetic radiation includes AM/FM radio waves, microwaves, heat, visible light (red to violet), ultraviolet radiation, X rays, and gamma rays.

Electromagnetic radiation types are identified based on their **frequency, wavelength**, and source. The energy sources that produce EMR vary greatly, from nuclear reactions in the Sun, which generate gamma radiation, to chemical reactions in the human body that generate infrared radiation (heat).

EMR is produced by the acceleration of charged particles resulting in transverse waves of changing electric and magnetic fields that can travel through space without the need of a material medium. All forms of EMR travel at the same speed, commonly referred to as the speed of light (c, in a vacuum), equal to 3.00×10^8 m/s.

EMR does not always travel directly from the source to the observer. As a result, it can be observed in one of two ways:

directly from the source

indirectly, as reflected or transmitted radiation

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Seeing is a photochemical process that is sensitive to certain wavelengths of electromagnetic radiation. When EMR is absorbed by the tissues in the human eye, a compound called *retinal* changes in physical form from bent to straight. The retinal molecule, in turn, is connected to a membrane-bound protein called *opsin* forming the complex molecule called *rhodopsin*. When the retinal molecule changes its form, it separates from the rhodopsin and the opsin triggers a nerve cell to signal the brain that light has been seen.

Burning magnesium (Figure 13.3) allows both methods of observing radiation. Other objects, such as the text you are reading now, do not produce radiation. You are able to read the text because it is reflecting radiation (light) from another source. If you are wearing glasses, this radiation is transmitted through your lenses.

The evidence obtained in 13-1 QuickLab indicates one unique characteristic of electromagnetic radiation. However, visible light, radiant energy that the eye can detect, only makes up a small portion of the spectrum of EMR present in our universe.

▲ **Figure 13.3** When magnesium burns, you can observe radiation directly from the reaction and indirectly from the radiation that is reflected from the smoke.

Concept Check

Can infrared radiation reflect off objects and be observed by the human body? Explain and give examples.

Types of Electromagnetic Radiation

The **electromagnetic spectrum** is the term applied to all the types of EMR considered together in terms of frequency, wavelength, or energy. All parts of the spectrum are found, with varying intensity, in our natural environment. We are most familiar with the visible spectrum since we sense it directly with our eyes. The infrared spectrum is sensed as heat and the ultraviolet spectrum includes radiation that can damage living cells, often causing a physiological response such as sunburn. Other parts of the spectrum may be present as background radiation. Natural background radiation originates from two primary sources: cosmic radiation and terrestrial sources. Cosmic radiation from deep space interacts with atoms in the atmosphere producing X rays and unstable isotopes. Terrestrial sources of gamma radiation include radioactive isotopes of uranium, radon, potassium, and carbon. Also, above-ground nuclear tests of the 1940s–1960s combined with nuclear accidents such as Chernoybl have scattered a substantial amount of radioactive material within our environment. Figure 13.4 shows the overlap of frequencies and wavelengths among the different forms of EMR in the electromagnetic radiation spectrum.

electromagnetic spectrum: all types of EMR considered in terms of frequency, wavelength, or energy

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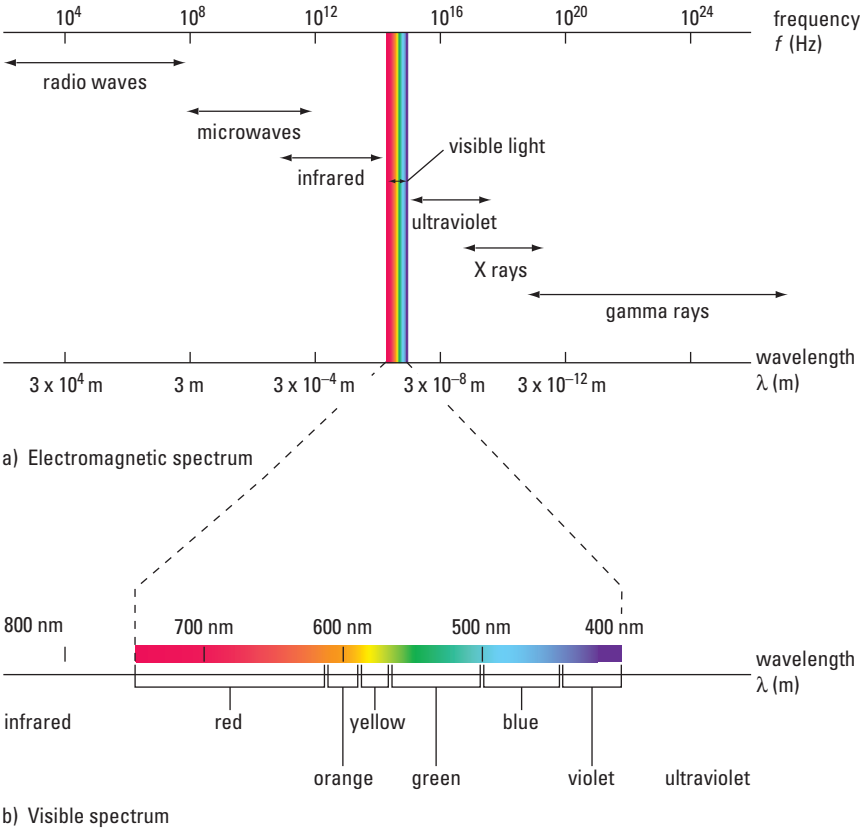
To learn more about the different types of EMR and the trends seen across the spectrum, follow the links at www.pearsoned.ca/school/physicssource.



▲ **Figure 13.4** The electromagnetic radiation spectrum showing the visible range

The relative energy of the different types of EMR varies with frequency across the spectrum. Table 13.1 compares the various sources and characteristics of the radiation found in the EMR spectrum.

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To learn more about the medical uses of different types of EMR, follow the links at www.pearsoned.ca/school/physicssource.

▼ **Table 13.1** The Electromagnetic Spectrum: Characteristics

Type of Electromagnetic Radiation	Method of Production	Characteristics	Problems
Alternating Current Power $f = 60$ Hz $\lambda = 5.0 \times 10^{6}$ m relative energy: insignificant	oscillation of electrons in alternating current	extremely long wavelength; while the AC power has many familiar uses, the 60-Hz wave emitted has no known uses at present	interference with other local EMR waves
Radio and Radar $f = 10^{4} - 10^{10}$ Hz $\lambda = 10^{4} - 10^{-2}$ m relative energy: very low	oscillation of electrons in an electric circuit like an antenna	long wavelength allows a large amount of diffraction making it useful for long-distance communication, e.g., cell phones, PC broadband	requires government regulations to control transmission and avoid interference
Microwaves $f = 10^{9} - 10^{12}$ Hz $\lambda = 10^{-1} - 10^{-4}$ m relative energy: low	oscillation of electrons in special tubes and solid state devices	shorter wavelength reduces diffraction for short-distance communication; frequency matches the natural resonant frequency of water molecules; used in microwave ovens	may be linked to some forms of cancer; causes damage to living tissue due to heating of water molecules within tissues
Infrared $f = 10^{11} - 4.0 \times 10^{14}$ Hz $\lambda = 10^{-3} - 7.5 \times 10^{-7}$ m relative energy: low	transitions of valence shell electrons in atoms and molecules	causes object absorbing it to become warm; used for remote sensing, night vision scopes, and identification of sources of heat	significant exposure can burn tissue
Visible $f = 4.0 \times 10^{14} - 7.5 \times 10^{14}$ Hz $\lambda = 7.5 \times 10^{-7} - 4.0 \times 10^{-7}$ m relative energy: medium	higher-energy transitions involving valence electrons in atoms	reflects off small objects, making them visible; diffracts around very small objects, making them invisible	limits the size of objects that can be seen
Ultraviolet $f = 7.5 \times 10^{14} - 10^{17}$ Hz $\lambda = 4.0 \times 10^{-7} - 10^{-9}$ m relative energy: high	even higher-energy transitions involving valence electrons in atoms	easily absorbed by objects; causes fluorescence of some materials, tanning in humans; kills bacteria	may cause sunburn; prolonged exposure can cause mutations and cancer in humans
X ray $f = 10^{17} - 10^{20}$ Hz $\lambda = 10^{-9} - 10^{-12}$ m relative energy: very high	transitions of electrons in an atom or the sudden acceleration of high-energy free electrons	penetrates most matter and is absorbed by denser material (like bone or metal); destroys carcinogenic or mutant cells; used for medical imaging in humans and in industry	can cause mutations and cancer in humans
Gamma $f = 10^{19} - 10^{24}$ Hz $\lambda = 10^{-11} - 10^{-16}$ m relative energy: extremely high	decomposition of unstable nuclei, either spontaneously or by the sudden negative accelerations from high-energy particle accelerators	penetrates matter very deeply; destroys carcinogenic or mutant cells on a local scale; used to probe the structure of matter and in industrial imaging	can cause radiation sickness and death
Cosmic $f = 10^{24}$ Hz and greater $\lambda = 10^{-16}$ m and less relative energy: extremely high	bombardment of Earth's atmosphere by extremely high-energy particles from space	penetrates matter very deeply; study of cosmic rays allows investigators to formulate ideas about the universe	can cause radiation sickness and death

Competing Models of Electromagnetic Radiation

Historically, investigators have tried to explain transmission, reflection, refraction, and absorption, and the other characteristics common to all types of EMR by using models. The historical **particle model** describes EMR as a stream of tiny particles radiating outward from a source. A **particle** is a discrete unit of matter having mass, momentum (and thus kinetic energy), and the ability to carry an electric charge. The particle model of EMR is the most simplistic of all the models. It is supported by the facts that EMR propagates in straight lines, can be reflected, and can be absorbed. The pool ball (particle) in Figure 13.5 exhibits particle characteristics. It can travel in a straight line, obey the law of reflection when it bounces off a side rail, and be absorbed by the table when it drops into a pocket.

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The Particle Theory of Light, also known as the Corpuscular Theory of Light, was put forward in Newton's *Opticks*, published in 1704.

particle model: describes EMR as a stream of tiny particles radiating out from a source

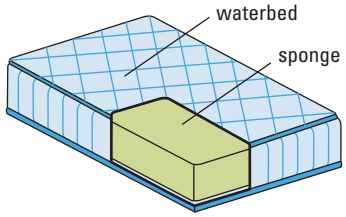
wave model: describes EMR as a stream of transverse waves radiating out from a source

▲ **Figure 13.5** A pool ball on a pool table exhibits the particle characteristics of linear movement, reflection, and absorption.

▲ **Figure 13.6** A water wave is a transverse wave that transfers energy in the form of a disturbance.

A second model, the **wave model,** describes EMR as a stream of transverse **waves** radiating outward from a source. As you learned in Chapter 8, a wave is a transfer of **energy** in the form of a disturbance. The energy transfer usually occurs in, but is not limited to, a material medium like water. A water wave travels in a straight line, reflects from surfaces, and can be absorbed (Figure 13.6). For example, water waves, which continually reflect inside a waterbed, transfer unwanted energy that can be absorbed by a sponge (Figure 13.7). EMR, however, does not require the presence of a medium.

The modern wave model of light has its origins in the 17th century when the Dutch mathematician and scientist, Christiaan Huygens argued that light consisted of waves. He suggested light waves could interfere to produce a wave front, travelling outward in a straight line. At the time, however, Huygens' wave theory was overshadowed by the immense scientific popularity of Newton's particle theories. The wave model gained further support from evidence produced by the work of Thomas Young (Figure 13.8) and his now-famous two-slit experiment of 1801. The details and implication of the experiment are set out in section 13.5, but in general, Young was able to show that a beam of light, when split into two beams and then recombined, shows interference effects that can *only* be explained by assuming that light has wavelike properties.



▲ **Figure 13.7** Waves in a waterbed exhibit the wave characteristics of linear movement, reflection, and absorption.

▲ **Figure 13.8** Thomas Young (1773–1829)

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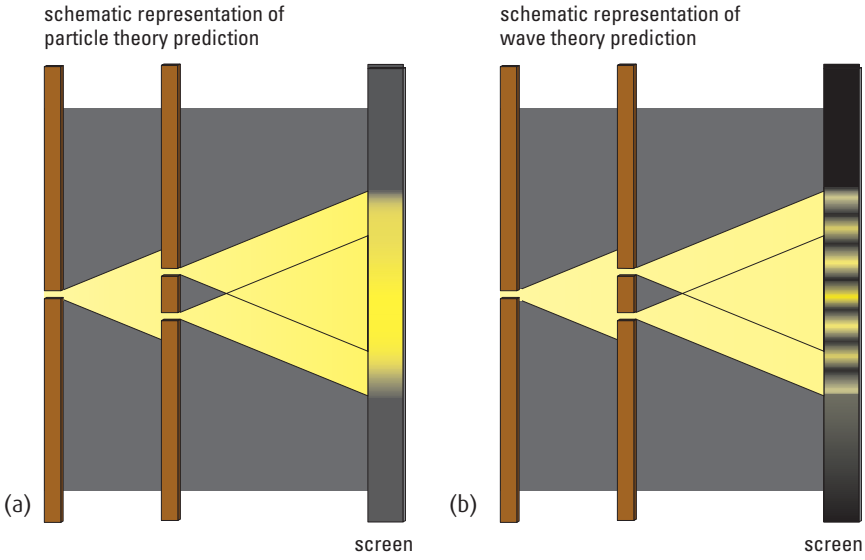
To learn more about Young's experiment and its relationship to the models of EMR, follow the links at www.pearsoned.ca/school/physicssource.

If light behaves as a particle, then one would expect to observe a bright region wherever the light emanating from the slits reaches a distant screen (Figure 13.9(a)). But Young obtained a result similar to that shown in Figure 13.9(b), where a pattern of light of varying intensity is observed after the light passes through the two slits. This pattern is similar to two-source interference patterns in water waves, as seen in section 8.3. Young's experiment thus presented strong evidence for the wave model of light.



▲ **Figure 13.9** When light is incident on two small slits, it is diffracted as it passes through each slit and an interference pattern is observed that supports the wave model of light.
a) A schematic representation of the particle theory prediction
b) A schematic representation of the wave theory prediction

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A quantum is a discrete unit of energy. The term originates from the Latin *quantus*, which means "how much." "**Quanta**" is the plural of "quantum." The Quantum Theory was so revolutionary that its formulation distinguishes the shift from classical physics to what we now call modern physics.

Planck and Einstein

By the end of the 19th century, both the particle and wave models of EMR were supported by scientific evidence. In 1900, Max Planck (1858–1947) proposed a radically new model to explain the spectrum of radiation emitted from a perfectly black object. In a mathematical derivation Planck assumed that all of the vibrating molecules, "oscillators," in the black body could vibrate with only specific, discrete amounts of energy. In doing so, he had to ignore the continuous distribution of energy of classical physics and introduce the concept of **quanta,** or discrete packets of energy. Planck was awarded the Nobel Prize for Physics in 1918, "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta."

In 1905 Einstein extended this quantum theory by proposing that light is emitted in quantized, tiny, *massless* particles, which are now called **photons.** Planck's original theory thus evolved into the currently accepted **quantum model** of light, which is a combination of both the particle and wave models. This model describes light and all other electromagnetic radiation as discrete bundles or "packets" of energy. Each packet, or photon, is a particle that has wave characteristics. In the quantum model, EMR has two aspects of behaviour, one being

photon: (from the Greek word meaning "light"); a discrete packet of energy associated with an electromagnetic field

quantum model: a combination of the particle and wave models. It describes light and all other EMR as discrete bundles of energy, each of which is a massless particle that has wavelike characteristics.

wavelike and the other being particle-like. Quantum theory reconciled these two types of behaviour while, at the same time, challenging both the classical wave and particle models.

Planck's quantum idea challenged the wave model by proposing that EMR does not deliver energy in a continuous form as a wave would, but rather, it delivers energy in small bundles. At the same time, his idea challenged the particle model by limiting the energy of the particles to certain discrete values, a condition not possible for a Newtonian particle.

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To learn more about Max Planck, begin your search at www.pearsoned.ca/school/physicssource.

Concept Check

Consider the wave model of light and the particle model of light.

1. Which of the following best describes the word "model"?
   (a) simplified description of a complex entity or process;
   (b) a representation of something on a smaller scale;
   (c) both a and b.
2. Explain your answer from part 1 and provide several examples of models that are used in a similar way.
3. The EMR spectrum includes many classes of radiation. Describe the wave characteristics used to classify each type of radiation on the spectrum. How are these characteristics related to the energy of the radiation?

Project LINK

How will you present the observations and theoretical concepts that culminated in the ideas of Planck and Einstein?

Maxwell's Electromagnetic Theory, 1865

In 1865, James Clerk Maxwell (1831–1879) proposed his Electromagnetic Theory, which synthesized earlier ideas and theories with the results of experiments to provide a theoretical framework for future studies. Maxwell proposed the idea that a changing **electric field** produces a changing **magnetic field** and that the interaction between these fields propagates as a wave through space. In his theory Maxwell linked concepts of electricity and magnetism so that we now call them "electromagnetic."

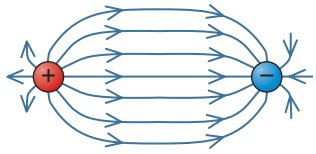
electric field: a three-dimensional region of electrostatic influence surrounding a charged object

magnetic field: a three-dimensional region of magnetic influence surrounding a magnet

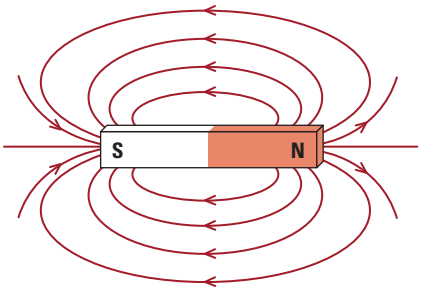
Maxwell based his theory on key phenomena observed by earlier investigators of electricity and magnetism. You have already met these ideas in Unit 6, but we will restate them here to appreciate the importance of Maxwell's contribution.

The Concept of the Electric Field

As Faraday had proposed and as you saw in Chapter 11, an electric field surrounds any charged particle and an electrostatic force will act on another charged particle when it is placed in that field. The electric field strength can be calculated and electric field lines drawn to illustrate the region of influence. Electric field lines begin and end at a charge (Figure 13.10) and the number of field lines passing through any closed surface is determined by the total charge enclosed by the surface. This concept allows the idea of interaction between particles at a distance, even though there is no contact between them.



▲ **Figure 13.10** Electric field lines are used to illustrate the region of influence between two oppositely charged particles.



▲ **Figure 13.11** The number of magnetic field lines that exit a magnetic material is equal to the number of magnetic field lines that enter a magnetic material — forming a closed loop.

The Concept of the Magnetic Field

A magnetic field (as discussed in Section 12.1) is a three-dimensional region of magnetic influence surrounding a magnet. Magnetic field lines form a closed loop and represent the direction and magnitude of the magnetic field (Figure 13.11).

Relationships Between Electricity and Magnetism

Electrical current in a conductor *produces* a magnetic field perpendicular to the current (Oersted, Unit VI, page 587) and the strength of the magnetic field depends on the magnitude of the current (Ampere, Unit VI, page 607). This relationship is known as Ampere's Law.

Inversely, moving a conductor connected in a circuit through a magnetic field *induces* an electric current. The magnitude of the electrical current is directly related to the rate of change in the magnetic field (Faraday and Henry, Unit VI, page 611). This relationship is known as Faraday's Law.

capacitor: two conductors, holding equal amounts of opposite charges, placed near one another without touching

Maxwell's Equations: a series of equations that summarized the relationships between electricity and magnetism and predicted the existence of electromagnetic waves and their propagation through space

Putting the Laws of Electromagnetism Together

From this basis and through his work with capacitors, Maxwell developed the laws of electromagnetism. Maxwell's work with capacitors showed that the electric field produced by a **capacitor** could have the same effect as a moving charge. In other words, a changing electric *field* will produce a changing magnetic field in the same manner as a changing electric current can produce a changing magnetic field. This information was extremely important because it showed that a conductor is not necessary for an electromagnetic wave to exist.

Maxwell put these ideas together with incredible ingenuity using calculus, which is beyond the scope of this text. His theory is embodied in a series of equations known as **Maxwell's Equations.**

To visualise the relationship between the electric and magnetic fields, we will proceed stepwise. Begin with a plane transverse wave that shows an electric field of varying strength (Figure 13.12). Next, consider two of the electric field lines on the transverse wave, an upward one at one location and the corresponding downward one at another. Imagine a path connecting the tips of these two electric field vectors, as shown by the dotted line in Figure 13.13. You can see that the electric field changes direction continuously from one direction to the opposite direction along a "closed path."

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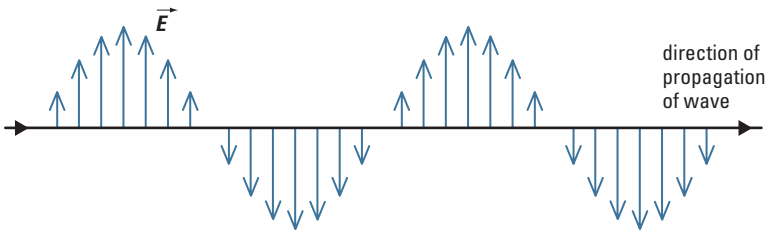
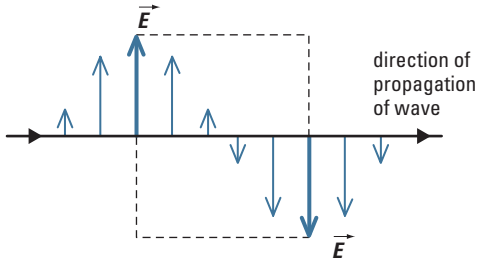
Maxwell was working with a system of units for electromagnetic theory, referred to as the CGS system. This system was derived from the base units of centimetre, gram, and second. The CGS system has largely been replaced by the SI system, based on the metre, kilogram, and second.



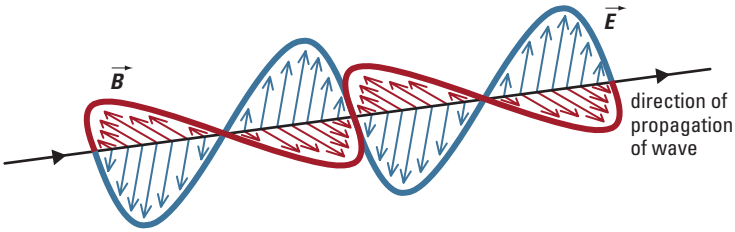
▲ **Figure 13.12** Plane transverse wave showing the electric field lines.



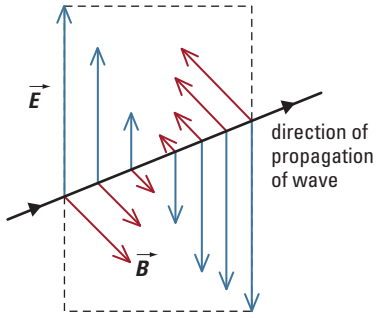
▲ **Figure 13.13** A path connecting two oppositely directed electric field lines on the transverse wave shows the change in the electric field.

Now, consider the magnetic field that exists perpendicular to the electric field along this closed path. When the electric field is set in motion, the magnetic field will change along with the electric field, and similarly along a closed path. An electromagnetic wave will propagate in a direction perpendicular to both fields (Figure 13.14).

The changing electric and magnetic fields will propagate, or radiate, through space in the form of a wave — an **electromagnetic wave** (Figure 13.15). Maxwell proposed that the electromagnetic wave consists of periodic variations in the electric and magnetic field strengths and that these variations occur at right angles to one another as the wave propagates.



▲ **Figure 13.15** Three-dimensional view of an electromagnetic wave



▲ **Figure 13.14** The magnetic field lines (in red) allow us to visualize the magnetic field that exists perpendicular to both the electric field and the direction of the wave.

electromagnetic wave: periodic variation in perpendicular electric and magnetic fields, propagating at right angles to both fields

Maxwell's Predictions

Maxwell's equations not only correctly predicted the existence of electromagnetic waves, but also allowed him to make some predictions about the waves' properties.

1. Electromagnetic waves are produced whenever an electric charge is accelerating. Therefore, as an electric charge oscillates, electrical energy will be lost, and an equivalent amount of energy will be radiated outward in the form of oscillating electric and magnetic fields.
2. When the electric charge is accelerated in periodic motion, the frequency of oscillation of the charge will correspond exactly to the frequency of the electromagnetic wave that is produced.
3. All electromagnetic waves will travel at a speed of 310 740 000 m/s and obey the universal wave equation ($c = f\lambda$) relating speed, frequency, and wavelength. (Note that Maxwell's theoretical prediction was not far from today's currently accepted value of 3.00×10^8 m/s for the speed of light in a vacuum.)
4. The oscillating electric and magnetic fields will always be perpendicular to each other and perpendicular to the direction of propagation of the wave.
5. Electromagnetic waves should show all the phenomena associated with transverse waves: interference, diffraction, refraction, and polarization.

It is Maxwell's last prediction that supports the wave model of EMR and relates his predictions to experimental evidence. Interference, diffraction, polarization, and refraction, as they relate to the wave model of EMR, will be explored in sections 13.4 and 13.5.

eWEB

To learn more about ways of representing the relation between electric and magnetic fields, follow the links at www.pearsoned.ca/school/physicssource. Compare and contrast the representations you find.

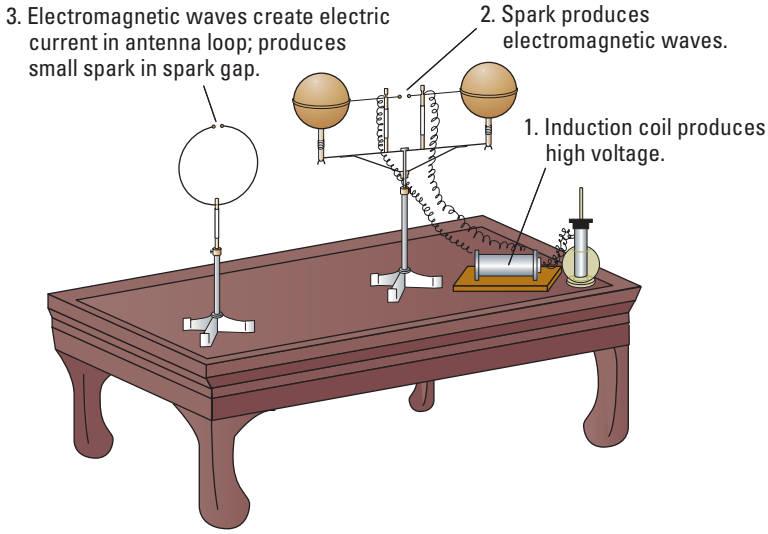
Producing Electromagnetic Radiation — The Story of Accelerating Charge

In 1887, the German physicist Heinrich Hertz (1857–1894) set up an experiment designed both to produce and to detect EMR. In his experimental apparatus, Hertz used a radiator, consisting of a pair of wires attached to both a high-voltage induction coil and a pair of capacity spheres. The wires were separated by a small gap and, given a sufficient quantity of opposite charge on each wire, a current would oscillate back and forth across the gap at a frequency of 10^9 Hz. With each oscillation a spark was produced when the moving charge ionized the air molecules on its way from one wire to the other.

From Maxwell's equations Hertz knew theoretically that this rapidly-moving electric charge should produce EMR. A short distance away from the radiator a collector plate containing a small loop of wire, the antenna, was observed to detect the effect of EMR. While the radiator was in operation and when the radiator and the antenna were tuned to the same frequency, a spark was observed at the antenna indicating a potential difference and an electric current (Figure 13.16).

eWEB

To learn more about details of Hertz's experiment, follow the links at www.pearsoned.ca/school/physicssource.


3. Electromagnetic waves create electric current in antenna loop; produces small spark in spark gap.
2. Spark produces electromagnetic waves.
1. Induction coil produces high voltage.

▲ **Figure 13.16** Hertz's apparatus consisted of a high-voltage induction coil, a radiator that produces sparks, and an antenna loop.

Relating Theory and Practice in Hertz's Experiment

The word "changing" appears a number of times in Maxwell's original proposal. As Maxwell understood it, a "changing" electric field was crucial to creating an electromagnetic wave. This is where the induction coil was important in Hertz's experimental design. The induction coil rapidly changed the electric field across the spark gap. When this electric field reached a sufficiently high value, the electrons in the wire "jumped" from one electrode to the other. As the charge was rapidly transferred, the electric field underwent a rapid change that caused a changing magnetic field, which then caused a changing electric field, and so on. An electromagnetic wave was produced and it radiated outward in all directions.

In Hertz's experiment, when the receiver was tuned to the same frequency as the radiator, the induced current flow in the antenna oscillated at a frequency identical to that of the changing electric field in the radiator. This was conclusive evidence that Hertz's device had indeed produced the EMR that was being observed at his antenna. Furthermore, he was able to measure the velocity of the waves by using a zinc reflector plate to produce a standing wave and moving a ring antenna within the standing wave. He could determine the magnitude and direction of the wave's components and therefore the wavelength. Given the frequency of the radiator, the velocity of the wave could be calculated using the universal wave equation ($v = f\lambda$).

Hertz had produced and measured the wavelength and velocity of *non-visible* EMR for the first time. Two years later, in 1889, radio pioneers used this method to transmit the first radio waves across the English Channel. By 1901, the first radio waves were transmitted across the Atlantic Ocean from Cornwall, England to St. John's, Newfoundland and a new age of technology had dawned. The production of EMR was one of the greatest scientific achievements of the 19th century, ushering in new possibilities and technologies that are commonplace today.

e WEB

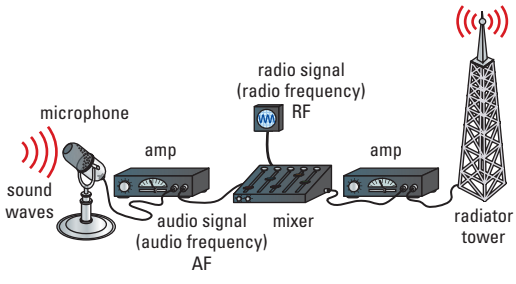
To learn more about Marconi and details of the first trans-Atlantic radio transmission, follow the links at www.pearsoned.ca/school/physicssource.

MINDS ON Going Wireless

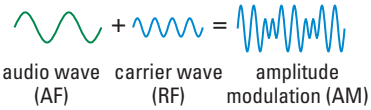
Wireless communication systems that transmit data are commonplace today.

1. Create a list of wireless data transmission technologies.
2. What process must be common to all wireless transmission devices?
3. What variable is used to control the acceleration, and hence the energy, of the accelerating electrons in a wireless device?
4. One radio transmission tower transmits at 5.0 kV. Another transmits at 10.0 kV. Which tower has a greater signal strength and why?
5. Cell phones communicate with cell towers that are dispersed throughout urban cities and transportation corridors. Explain the relationship between the distance that separates a cell phone from the nearest cell tower and the operating power of the cell phone.
6. Many studies have been conducted to investigate and determine if there is a relationship between brain cancer and cell phone usage. Why would one suspect a relationship between cell phone use and brain cancer?

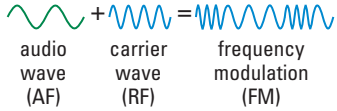
Although modern radio signals are generated without a spark, the technology operates in a way similar to Hertz's original experiment. Radio waves are generated by rapidly changing the electric potential, or voltage, in the radiator tower. The oscillating voltage produces an oscillating electric field in the radiator tower (Figure 13.17).



▲ **Figure 13.17** Schematic of a simple radio transmitter



▲ **Figure 13.18** Amplitude modulation. The audio signal and the carrier signal are mixed by modifying the amplitude of the carrier signal.



▲ **Figure 13.19** Frequency modulation

Analog Radio Technology

The first application of Hertz's discovery was made by Guglielmo Marconi (1874–1937). He recognized the potential for transmitting information using electromagnetic waves, by coding the information into dots and dashes, like the Morse code already used in telegraphy. Today, the dots and dashes have been replaced by an analog signal, which uses a continuous spectrum of values.

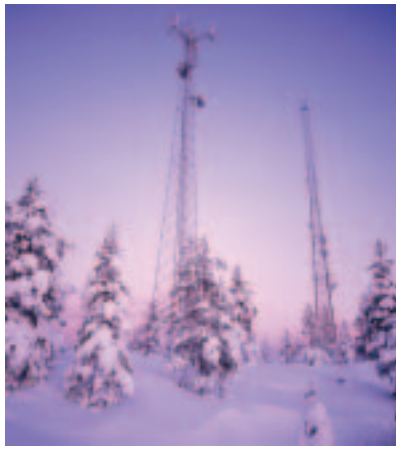
In radio, sound waves in the range of 20–20 000 Hz (audible to humans) are converted into a weak electrical signal in an analog form. This wave is called the audio frequency signal (AF). The weak audio frequency is then amplified and sent to a mixer. In the mixer, a radio frequency (RF) called a carrier signal, is added to the audio signal to produce an analog wave that contains two sets of information: the audio signal and the carrier signal. The carrier signal frequency is determined by the government and is unique to that station for that broadcast area. It is the carrier signal that you select when you tune your radio to the station.

Finally, the mixed signal is amplified and delivered to the radiator tower, where the movement of electrons through the radiator wire will produce the corresponding form of electromagnetic wave (Figure 13.17). Television signals follow the same process, except that the video and audio portions are transmitted separately.

Radio reception is accomplished by tuning the radio to the carrier signal and then removing, or demodulating, the wave. This reveals the audio signal, which is amplified and delivered to the speakers.

AM or FM Radio?

The mixing of the audio signal and the carrier signal occurs in one of two ways. The first is called amplitude modulation or AM (Figure 13.18). The second method is called frequency modulation or FM. The audio signal and the carrier signal are mixed by modifying the frequency of the carrier signal (Figure 13.19).



▲ **Figure 13.20**

Digital Wireless Cell Phones

The cell phone and text messaging technology of today operates on a very different set of principles.

When a cell phone is switched on it registers with the mobile telephone exchange using a unique digital identifier. Once it has been identified it stays connected to a cellular network of ground-based stations, commonly referred to as cellular tower base stations, which can be found on radio towers, buildings, in church steeples, or any location which is free of physical obstacles and interference. Figure 13.20 shows one such cellular tower base station.

A cell phone communicates with the cell tower base station using radio waves. In turn the base station relays all information to and from the cell phone to another subscriber of the same cell phone network or through an interconnected public switched telephone network that uses fibre optic and copper land lines to transmit the data.

When in use, a cell phone converts the analog voice signal of the person talking into a stream of digital data, which is received by the nearest cell tower base station that may be anywhere from 0.8 –13 km away.

Each cell tower site has a low-power radio broadcast which can be picked up by cell phones. As the user moves, the cell phone constantly monitors the signals being received from various nearby cell tower stations, switching from one tower to another in such a way that the signal strength remains as high as possible.

The stream of digital data is unique to each type of network technology and each operator is assigned a different radio frequency so that several networks can operate simultaneously at the same location and they will not interfere with one another.

Wireless Technology for the Future

Future uses of cellular phone technology are emerging in the market place as the networks evolve and consume broadcast frequencies formerly occupied by some television channels. New entertainment features will include:

streaming video;
music downloads;
podcasts;
smooth speech recognition and language translations;
ebook features that use projection;
barcode readers that direct users to Internet urls;
global positioning systems and mapping combined with accelerometers to measure position and movements of the cell phone user.

Questions

1. Explain how cell phone user data, including geographical position and movement, could be considered an invasion of privacy.
2. How can multiple cell phone networks and traditional radio broadcasts all exist in the same geographical location and not interfere with one another?
3. Compare the carrier frequency of radio broadcasts with the unique digital identifier of a cell phone. What common purpose do they both serve?
4. Explain why a cell phone only works in certain areas and how changes in the signal strength will be observed by the cell phone user as he or she moves.

Concept Check

1. Consider two electric field lines on a transverse electromagnetic wave. Explain how a changing electric field will produce a changing magnetic field.
2. Why can electromagnetic radiation propagate through empty space, in the absence of a conductor?
3. An electromagnetic wave is produced if an electric charge accelerates. Explain how these two phenomena are linked.

13.1 Check and Reflect

Knowledge

1. List two ways that electromagnetic radiation is detected.

2. List the different types of EMR in the spectrum and the ways in which they are classified.

3. Define EMR using the

(a) particle model

(b) wave model

(c) quantum model

4. Describe the evidence that Thomas Young obtained from the two-slit experiment and explain how it supported the wave model of light.

5. Explain how the observations made by Hertz support the electromagnetic theories of Maxwell.

6. How did Maxwell's study of capacitors add to his theories?

7. Why is the process of "changing" critical to the production of EMR?

Applications

8. A high-voltage spark gap produced sparks with a frequency of 2.5×10^3 Hz. What is the frequency of the EMR observed at an antenna located nearby?

9. What properties need to be considered when choosing the material to build an antenna for a radio receiver?

10. If the magnetic field lines held within a closed path are constant and unchanging, will there be an electric field along the closed path? Explain.

11. If an electric charge is not moving, will it produce a magnetic field? Explain.

12. Explain why it is necessary for the technician to leave the room or wear protective clothing when a patient is being X rayed.

13. Describe how an antenna is affected by an electromagnetic wave.

14. Describe one method used to produce EMR with a known frequency.

Extensions

15. Explain, with the aid of a transverse standing wave diagram, how the current in a ring antenna (such as the one used by Hertz) will be affected as the antenna is moved along the axis of the standing wave. How could this data be used to determine the wavelength of the standing wave?

16. Draw a schematic that shows, in general terms, the role of a satellite in delivering digital, high-definition, television signals between the signal provider and the customer's home receiver.

eTEST

To check your understanding of the nature and production of electromagnetic radiation, follow the eTest links at www.pearsoned.ca/school/physicssource.

13.2 The Speed of Electromagnetic Radiation

info BIT

Maxwell predicted the speed of EMR before Hertz experimentally verified it. Maxwell knew that electric and magnetic fields are not independent of one another and predicted a speed of propagation by dividing the constants, k_e and k_m, which describe electric and magnetic forces between moving charged particles. Using today's currently accepted values of k_e and k_m, we can show that the magnetic field and the electrical field are related by a particular speed.

$$\frac{k_e}{k_m} = \frac{8.99 \times 10^9 \frac{N \cdot m^2}{C^2}}{1.00 \times 10^{-7} \frac{N \cdot s^2}{C^2}}$$

$$= 8.99 \times 10^{16} \frac{m^2}{s^2}$$

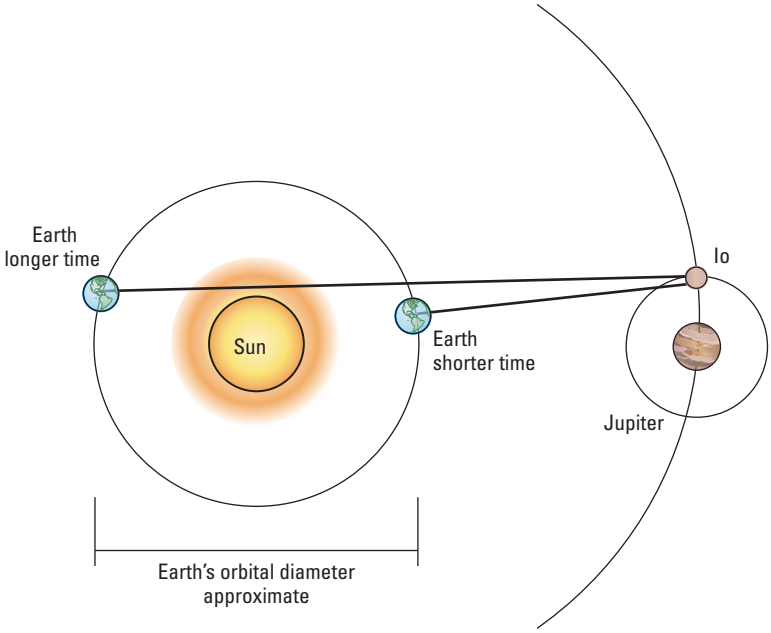
$$\sqrt{8.99 \times 10^{16} \frac{m^2}{s^2}} = 2.99 \times 10^8 \frac{m}{s}$$

In addition to producing and detecting electromagnetic radiation in his 1887 experiment, Hertz was able to show that the radiation was travelling at approximately 3.0×10^8 m/s. This was an empirical verification of a theoretical speed predicted by Maxwell years earlier, as described on page 643: All electromagnetic waves will travel at a speed of 310 740 000 m/s and obey the universal wave equation ($c = f\lambda$) relating speed, frequency, and wavelength.

Empirical Determination of the Speed of Electromagnetic Radiation

Light travels so quickly that there is no apparent time difference between turning on a light and the light reaching your eyes – even when the light source is many kilometres away. Galileo (1564–1642) found this out in his attempt to measure the speed of light. His experiment was very basic: Galileo and an assistant stood, each with a covered lantern, on adjacent hills separated by about a kilometre. Galileo would uncover his lantern and as soon as his assistant observed Galileo's lantern, he would uncover the second lantern so that Galileo would see it. Galileo used his pulse rate to measure the time difference. The time interval is actually extremely small – Galileo didn't know it at the time, but light could travel 2 km in about 0.000 066 67 s, a time you couldn't even measure with a digital stopwatch. Galileo realized that using his pulse as a timepiece was not appropriate.

Olaus Roemer (1644–1710) and Christiaan Huygens used one of the four easily visible moons of Jupiter to calculate the speed of light. The period of revolution for Io (Jupiter's brightest moon) had been accurately determined using large amounts of astronomical data collected over many years. Roemer knew that the moon Io should be eclipsed and disappear behind Jupiter at regular, periodic intervals (every 42.5 h). However, he discovered that Io appeared to be eclipsed later than scheduled when Earth was farther away from Jupiter and earlier than scheduled when Earth was closer to Jupiter. The time difference between the longest and shortest periods was 22 min (Figure 13.21).



▲ **Figure 13.21** Earth's orbital diameter causes the eclipse of Io to occur at different times because of the extra distance the light must travel when Earth is farthest from Jupiter.

Huygens reasoned that this discrepant behaviour could be due to the difference in the time taken for the light to travel from Jupiter to Earth. Following this reasoning, he estimated Earth's orbital diameter and then determined the speed of light based on the following calculations.

Orbital diameter $= 3.0 \times 10^{11}$ m

$$v = \frac{\Delta d}{\Delta t}$$

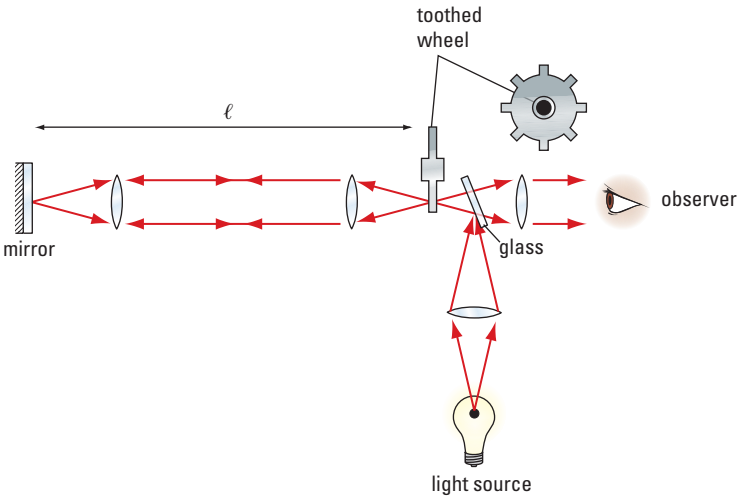
Time difference = 22 min = 1320 s

$$v = \frac{3.0 \times 10^{11} \text{ m}}{1320 \text{ s}}$$

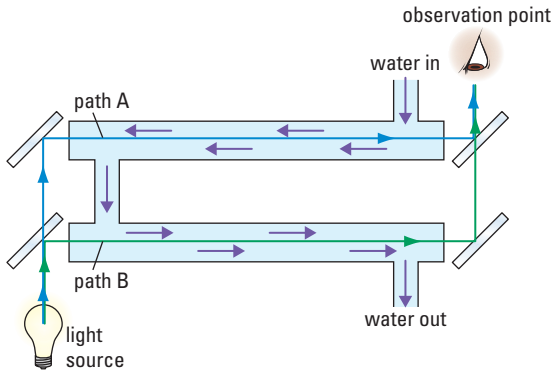
$$v = 2.3 \times 10^{8} \text{ m/s}$$

His calculations produced a value of 2.3×10^8 m/s — astoundingly close to the currently accepted value of 3.0×10^8 m/s. The value was so large it was rejected by the scientific community of the time and was not accepted until after both Huygens and Roemer were dead.

In 1848, Armand Fizeau became the first person to successfully measure the speed of light at the surface of the planet. His apparatus consisted of a rotating toothed wheel, a light source, some lenses, and a mirror. In his experiment, light was allowed to pass through one of the gaps on the toothed wheel and travel toward the mirror (located on an adjacent hill-top 8.63 km away) where it was reflected back toward the spinning wheel (Figure 13.22). The toothed wheel was rotated such that the reflected light was blocked by a tooth in the wheel as it turned, and the observer would not be able to see the source light. Using the rotational frequency of the spinning wheel, Fizeau was able to determine the time it took the light to travel 8.63 km and back (17.26 km round trip) and therefore to determine the speed at which the light was travelling to the distant mirror and back. His experimentally determined value for the speed of light was 3.15×10^8 m/s — only 5% more than the currently accepted value.



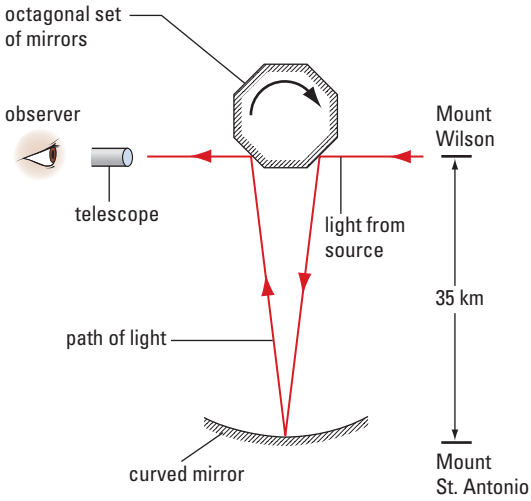
▲ **Figure 13.22** Fizeau's original apparatus for measuring the time it takes light to travel the distance ℓ (8.63 km) and back



▲ **Figure 13.23** Fizeau's apparatus for measuring the speed of light in water

Three years later Fizeau conducted an investigation to determine if the speed of light was affected by a moving medium such as water. In this experiment, water was pumped in opposite directions through two parallel tubes (Figure 13.23). Light from a single source was directed through both tubes, following paths A and B, of identical lengths, to an

observation point. Fizeau argued that if the speed of the light waves changed as a result of travelling through the water tubes, the waves arriving from path A and B would produce an interference pattern at the observation point. A device called an interferometer was used to observe this interference. The experiment proved that light would travel at different speeds in different media. The interference pattern produced was also very strong evidence that light was a wave.



▲ **Figure 13.24** Michelson's experimental apparatus to measure the speed of light

Michelson's Experiment

Building on Fizeau's 1848 experimental design and the work of others, Albert Michelson performed an experiment in 1905, using a rotating set of mirrors instead of a toothed wheel. A very intense light source was directed at an 8-sided, rotating set of mirrors, which reflected the light toward a curved mirror located 35 km away. After travelling 35 km, the light was reflected back toward the rotating mirrors. If the rotating mirrors had made 1/8th of a rotation just as the light returned, the returning light could be observed in a telescope (Figure 13.24).

For the returning light to be observed in the telescope, the rotating mirrors had to turn at a very precise frequency. Michelson knew the light had to travel a round trip distance of 70 km, and if the rotating mirrors had made 1/8th of a rotation (or a multiple of an 1/8th rotation) between the time the light left and then returned, the light could be observed in the telescope. All Michelson needed to measure was the frequency of rotation and he could determine the time required for 1/8th of a rotation. When his mirror rotated at 32 000 rpm (533 Hz), he could observe the light in the telescope.

Practice Problems

1. Students using a 12-sided set of rotating mirrors in an experiment similar to Michelson's determine the speed of light to be 2.88×10^8 m/s. The mirrors are located 30.0 km from the fixed mirror. What is the frequency of rotation?
2. Light reflected from an 8-sided rotating set of mirrors travels 15.0 km to a distant fixed mirror and back. At what frequency is the set rotating if it has turned 1/8th of a rotation before the light returns?
3. An 8-sided set of mirrors, similar to Michelson's, rotating with a frequency of 500 Hz, is located 36.0 km away from a fixed mirror. If the returning light is observed in the system, at what speed is the light travelling?

Answers

1. 400 Hz
2. 1.25×10^3 Hz
3. 2.88×10^8 m/s

Example 13.1

The set of rotating mirrors in Michelson's experiment was rotating at 533 Hz and the reflecting mirror was located 35.0 km away. Show how Michelson determined the speed of light from these data.

Given

$\Delta d = 35.0 \text{ km} \times 2 = 70.0 \text{ km}$, round-trip distance for light path

$\Delta d = 7.00 \times 10^4 \text{ m}$

$f = 533 \text{ Hz}$

Required

speed of light (c)

Analysis and Solution

$$c = \frac{\Delta d}{\Delta t}$$

The light must travel from the set of mirrors to the curved mirror and back again, so the round-trip distance is twice the given distance. $(3.50 \times 10^4 \text{ m})(2) = 7.00 \times 10^4 \text{ m}$.

For the light to follow the path illustrated in Figure 13.24, the rotating set of mirrors must complete a minimum of 1/8th of a rotation while the light is travelling between the rotating mirror and the curved mirror. Therefore, the minimum travel time (Δt) is equal to 1/8th of the period of rotation.

$$T = \frac{1}{f} \qquad \Delta t = \frac{1}{8}T \qquad c = \frac{\Delta d}{\Delta t}$$

$$T = \frac{1}{533\ \text{Hz}} \qquad \Delta t = \frac{1}{8}(1.876 \times 10^{-3}\ \text{s}) \qquad c = \frac{7.00 \times 10^{4}\ \text{m}}{2.345 \times 10^{-4}\ \text{s}}$$

$$T = 1.876 \times 10^{-3}\ \text{s} \qquad \Delta t = 2.345 \times 10^{-4}\ \text{s} \qquad c = 2.98 \times 10^{8}\ \text{m/s}$$

Paraphrase

According to Michelson's observations, the speed of light in air was found to be 2.98×10^{8} m/s.

13-2 QuickLab

Measuring the Speed of EMR

Problem

Microwaves are a type of electromagnetic radiation and travel at the speed of light. They have a defined wavelength and frequency when they travel in a vacuum or in air. The universal wave equation $v = f\lambda$ relates the speed of the wave to its frequency and wavelength, where f is the frequency of the radiation, and λ is the wavelength. Each microwave oven generates microwaves at a given frequency, usually 2450 MHz. If the wavelength of the microwave can be measured, its speed can be determined using the universal wave equation.

Materials

microwave oven
microwave-safe dish
marshmallows

Procedure

1. Pack a solid layer of marshmallows in a casserole or microwave-safe dish.
2. Remove the turntable from the microwave oven.
3. Place the dish in the oven and cook until the marshmallows begin to melt in four or five locations.
4. Remove the dish from the oven and measure the distance between adjacent soft spots.
5. Determine the average separation distance between several soft spots. This distance is equal to half the wavelength of a microwave.
6. Calculate the wavelength by multiplying the average separation distance by two.
7. Record the frequency of the microwave, which will be indicated on the back of the microwave oven.

Questions

Use the wavelength and frequency of the microwave to answer the following questions.

1. What is the speed of the microwaves?
2. What is the percent error of your calculated value, when compared with the currently accepted value for the speed of light (3.00×10^{8} m/s)?
3. What are several possible sources of error that could affect your calculation?
4. Compare the wavelength of microwaves with that of radio waves and visible light waves. Why are they called microwaves?

13.2 Check and Reflect

Knowledge

1. Why was Galileo's original experiment to determine the speed of light unsuccessful?
2. Explain why, in a Michelson-type experiment, the rotating mirrors have to turn at a very precise frequency in order for light to reach a stationary observer.
3. Explain why the periodic motion of Jupiter's moon Io appears to be constantly changing when observed from Earth.

Applications

4. In measuring the speed of light, the difference in eclipse times for Jupiter's moon Io, is measured. If eclipse occurs 24 min later than expected, and Earth's orbital diameter is 3.0×10^{11} m, calculate the speed of light.
5. A communications satellite is in orbit around Earth at an altitude of 2.00×10^4 km. If the satellite is directly above a ground-based station, how long does it take a signal to travel between the satellite and the station?
6. Using a similar approach to Michelson, a student sets up a 64-sided rotating mirror, 8.00 km away from a fixed mirror. What frequency of rotation would be required to successfully measure the speed of light?
7. A 16-sided rotating mirror is used to measure the time it takes light to travel a certain distance. At what frequency does the mirror need to rotate such that it makes 1/16th of a rotation in the time it takes light to travel 3.5 km and back again?
8. An 8-sided mirror rotates at 545 Hz in an experiment similar to that of Michelson. How far away should the fixed mirror be placed in order to correctly measure the speed of light?
9. The speed of light was measured to be 2.97×10^8 m/s using a 16-sided rotating mirror and a fixed mirror separated by 5.00×10^3 m. At what frequency was the mirror rotating?
10. Students who measure the speed of light using an experimental design similar to that of Michelson, make the following observations when light passes through the apparatus:
    (a) rotating mirror frequency $= 1.00 \times 10^3$ Hz
    (b) distance between fixed and rotating mirror = 17.5 km

    Determine the speed of light based on the students' recorded observations.
11. A 64-sided rotating mirror is turning at 340 Hz. If a fixed mirror is located 6.55 km away from the rotating mirror and the light is reflected correctly, what value for the speed of light would be obtained?

Extensions

12. Global positioning satellites (GPS) are used to pinpoint individual locations on the surface of Earth. A minimum of three GPS satellites are required, each with synchronized atomic clocks. Each satellite simultaneously sends a time signal to a GPS receiver on the surface. The time signal of each satellite is compared with the time on the receiver's clock.
    (a) Explain how the exact distance between each satellite and the receiver can be determined.
    (b) Explain how the receiver's location relative to all three satellites indicates an exact coordinate on Earth's surface.

eTEST

To check your understanding of speed and propagation of electromagnetic radiation, follow the eTest links at www.pearsoned.ca/school/physicssource.

13.3 Reflection

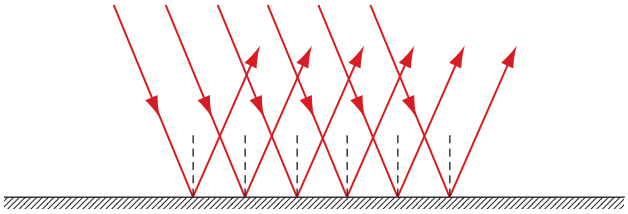
On a windless day, the smooth surface of a lake will reflect light and produce stunning images of the surrounding landscape and sky. But introduce the slightest disturbance, a gust of wind or a morning rain shower, and the image becomes distorted and blurred. With enough disturbance, the image on the surface of the water completely disappears.

▲ **Figure 13.25** a) Reflection in a smooth lake b) Diffuse reflection due to windy conditions

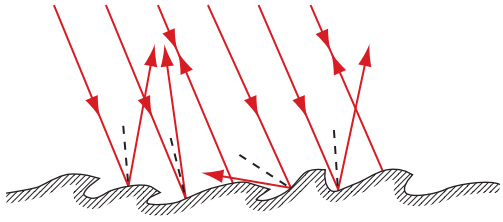
How do the images in Figure 13.25 form? Light travels in straight lines through a medium that is uniform. This characteristic is termed **rectilinear propagation.** The light falling on a flat, smooth, reflecting surface, such as a mirror, undergoes **specular** or **regular reflection.**

rectilinear propagation: movement of light in straight lines through a uniform medium

In the case of the smooth lake, the crisp, clear images that form are the result of many parallel incident rays that reflect as parallel reflected rays (Figure 13.26). In the case of the rough lake, the blurred images that form are the result of many parallel incident rays that are scattered after reflecting in many different directions. This behaviour is called **diffuse** or **irregular** reflection (Figure 13.27).



▲ **Figure 13.26** Ray diagram of specular (regular) reflection



▲ **Figure 13.27** Ray diagram of diffuse (irregular) reflection

The Law of Reflection

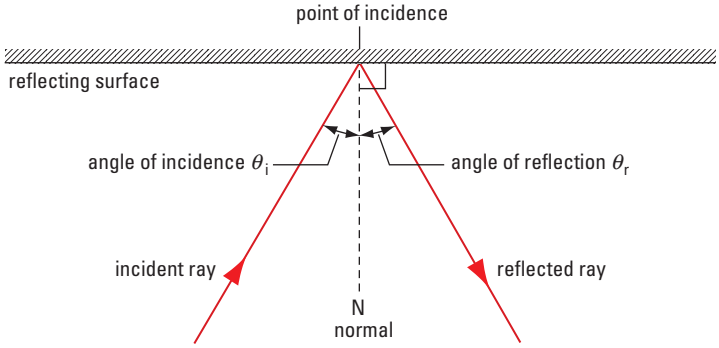
Particular terms are used to describe reflection. These terms are illustrated in the **ray diagram** shown in Figure 13.28 below. Regular reflection will occur when an **incident light** ray contacts a polished, reflecting surface. The incident ray makes contact at the **point of incidence** and then it leaves the reflecting surface and becomes the **reflected ray.** If, at the point of incidence, an imaginary line, called the **normal line (N),**

ray diagram: a diagram to show a result of a light ray interacting with a surface

eSIM

Find out more about the law of reflection from the use of simulations. Follow the eSim links at www.pearsoned.ca/school/physicssource.

is drawn perpendicular to the surface, then the angle formed between the incident ray and the normal line is called the **angle of incidence.** The angle formed between the reflected ray and the normal line is called the **angle of reflection.**



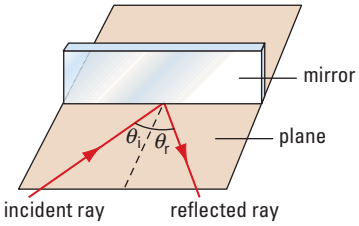
▲ **Figure 13.28** Ray diagram and terminology for regular reflection

Light rays that are incident upon a **plane mirror** at 90° will be reflected directly back to the source. In this case, the incident and reflected rays are parallel to the normal line so that the angle of incidence and the angle of reflection are both zero. In a similar way, when a light ray contacts a mirror at an angle of 25° relative to the normal line, it will reflect at an angle of 25° relative to the normal line. In all cases, the angle of incidence will be equal to the angle of reflection. This is called the **law of reflection** (Figure 13.29).

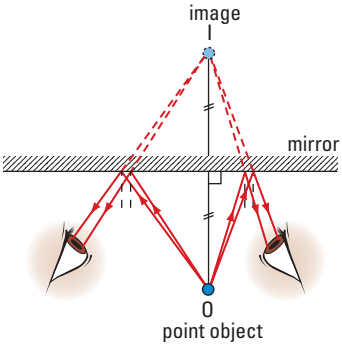
The angle of reflection is equal to the angle of incidence and is in the same plane.

plane mirror: a smooth, flat, reflecting surface

law of reflection: the angle of reflection is equal to the angle of incidence and is in the same plane



▲ **Figure 13.29**
The Law of Reflection



▲ **Figure 13.30** How two different observers see the image of an object located in front of a plane mirror

virtual image: an image from which light rays appear to come; cannot be formed on a non-reflective surface or screen

real image: an image from which light rays come; can be formed on a diffusely reflecting surface or screen

Image Formation in a Plane Mirror

Look at the image of an object formed in a plane, flat mirror in Figure 13.30. What do the dashed lines represent? Are they real rays coming from a real object? The dashed lines are an extension of the reflected rays, causing your eyes to "believe" that they are rays, originating from an object that is located behind the mirror. But this cannot be so. The light rays appear to be coming from an image, but this image is not real. The image formed in a plane mirror in this fashion is therefore called a **virtual image**. For example, if you were to hold a piece of paper behind the mirror where the image appears to be, you would not see the image on the paper. By contrast, a **real image** is one that can be formed on a diffusely reflecting surface, such as a piece of paper. A projector is a familiar device that produces real images on a screen. Ray diagrams can be used to show how images form with a reflecting surface, such as a mirror.

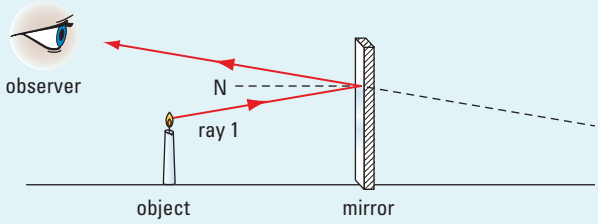
13-3 QuickLab

Drawing a Ray Diagram

Problem

To construct a ray diagram of an image formed in a plane, flat mirror.

Materials



▲ **Figure 13.31**

Procedure

1. Choose one point on the object, such as the tip of the candle flame, in Figure 13.31.
2. Draw an incident ray from the selected point on the object (adding a small normal line where the ray is incident on the surface of the mirror) (Figure 13.31).
3. Based on the law of reflection, the reflected ray leaves the mirror surface such that the angle of incidence is equal to the angle of reflection. Draw the reflected ray.
4. Use a dashed line to extend the reflected ray beyond the back surface of the mirror.
5. On your diagram, repeat steps 2 to 4 for a ray originating from the same location on the object, but at a slightly different angle.
6. Note that the viewer must be located where both reflected rays would enter the eye.
7. Repeat steps 2 to 6 and locate the point where the two dashed lines converge (meet). This is the image location for the first selected point on the object.

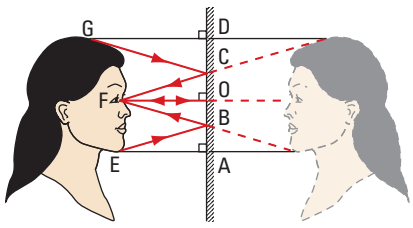
Questions

1. How could you test whether the image formed in the mirror was real or virtual?
2. Is the image magnified or the same size as the object?
3. Will the image appear right side up (erect) or upside down (inverted)?
4. Could you use a ray diagram to determine if the word "HELP" would appear backwards in a mirror? Explain.

MINDS ON Image in a Mirror

Figure 13.32 shows a woman looking in a mirror.

1. How far behind the mirror does her image form, if she is standing 50.0 cm in front of the mirror? Explain how the ray diagram is used to determine this distance.
2. Is the image real or virtual?
3. According to the ray diagram, two sections of the mirror could be removed and her entire face would still be visible. Which two sections are not needed? Explain your reasoning.



▲ **Figure 13.32** Woman in a Mirror

Image Characteristics

magnification: the relationship of the size of the image to the size of the object

image attitude: the orientation characteristic of an image, whether erect or inverted

When an object is placed in front of a mirror, the image can be described by four general characteristics (Table 13.2). The **magnification** relates the size of the image to the size of the object. The image can be enlarged, diminished, or the same size as the object. The **image attitude** describes the image as being either erect (upright) or inverted (upside down) relative to the object. This is termed vertical inversion. Horizontal, or left/right, inversion can also occur. The **position** describes where the image forms relative to the surface of the mirror. The **type** of image distinguishes between real and virtual images. A real image is one that can be caught or projected on a screen or surface, and a virtual image is one that can only be seen, or photographed.

▼ **Table 13.2** Image Characteristics

Image Characteristic	Description
magnification	same size, enlarged, diminished
attitude	erect or inverted
position	displacement from mirror surface
type	real or virtual

Image characteristics are important for the proper application of signage and warning labels. For example, the word "ambulance" is written in reverse on the front of the vehicle so that other drivers will be able to read the writing in their rear-view mirrors when the ambulance is approaching.

MINDS ON Image Characteristics

Figure 13.33 shows (a) an image of an ambulance and (b) its image in a rear-view mirror.

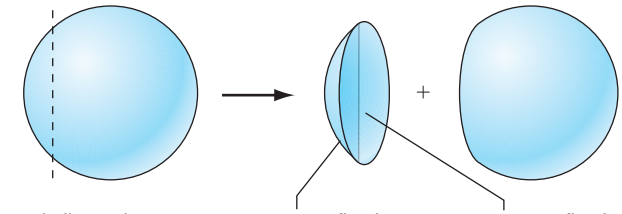
1. What image characteristic is addressed by printing the word "ambulance" in reverse?
2. While standing in front of a plane, flat mirror, raise your right hand. Which hand in your image was raised?
3. In a plane, flat mirror, do images appear backwards horizontally or upside down vertically or both? Explain.
4. Can an image in a plane mirror ever appear "upside down"?

▲ **Figure 13.33** (a) The front of an ambulance (b) The image it makes in a rear-view mirror

Image Formation in a Curved Mirror

Curved mirrors come in a variety of shapes, the most common being spherical. Spherical mirrors, like the ones used for store security, have a unique geometrical shape (Figure 13.34). This shape is derived from a sphere. Imagine a hollow sphere, with a polished mirror surface on the inside and out.

▲ **Figure 13.34** A spherical store security mirror



◄ **Figure 13.35**
A curved mirror can be formed from a hollow sphere.

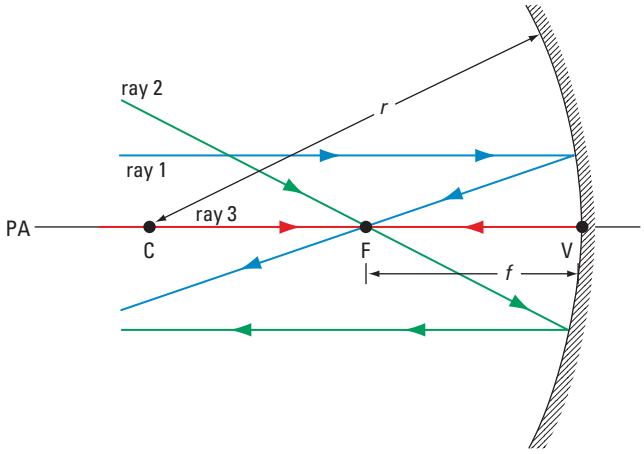
By removing a section of the sphere, you produce a double-sided spherical mirror with a concave reflecting surface on one side and a convex reflecting surface on the other (Figure 13.35). The concave reflecting surface is curved inwards. This surface is also referred to as a **converging mirror** since it causes parallel light rays to converge after being reflected. The convex reflecting surface is curved outwards. This surface is also referred to as a **diverging mirror** since it causes parallel light rays to spread out or diverge after being reflected.

converging mirror: a concave reflecting surface that causes parallel light rays to converge after being reflected

diverging mirror: a convex reflecting surface that causes parallel light rays to spread out after being reflected

As with plane-mirror image formation, ray diagrams are useful to determine how images form from curved surfaces. Ray diagrams for curved surfaces, as in Figure 13.36 for example, are more complex and involve an expanded set of terminology.

1. **centre of curvature (C)** – the point in space that would represent the centre of the sphere from which the curved mirror was cut
2. **radius of curvature (*r*)** – the distance from the centre of curvature to the mirror surface
3. **vertex (V)** – the geometric centre of the curved mirror surface
4. **principal axis (PA)** – an imaginary line drawn through the vertex, perpendicular to the surface of the curved mirror at this point
5. **principal focal point (F)** – the point where light rays that are parallel to and close to the principal axis converge, or appear to diverge from, after being reflected



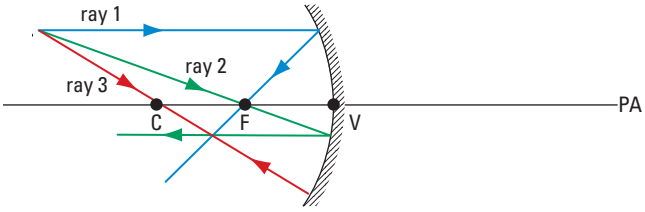
▲ **Figure 13.36** A ray diagram for a converging mirror

6. **focal length (*f*)** – the distance from the vertex to the focal point, measured along the principal axis. The focal length is related to the radius of curvature by $f = r/2$. This means that as the radius of curvature is reduced, so too is the focal length of the reflecting surface.

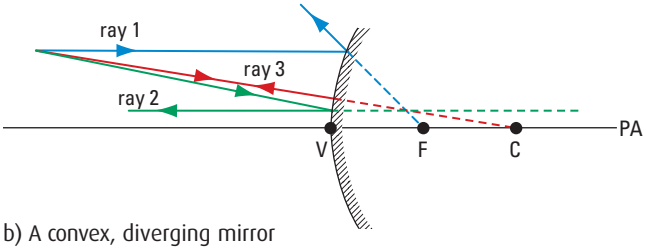
Drawing Ray Diagrams for Curved Mirrors

The four general image characteristics of magnification, attitude, position, and type, which were applied to plane mirrors, can also be applied to curved mirrors. For curved mirrors, the normal line at the point of incidence is the same as the radius of the spherical surface. The law of reflection still describes how all the rays will be reflected. To understand and predict how images are produced from curved mirrors, we will need to use three light rays, the law of reflection, and the mirror's focal point, centre of curvature, and vertex. Two rays from a point on an object locate the corresponding point on the image and the third ray will verify its location (Figure 13.37).

▼ Figure 13.37 Reflection of three rays from spherical mirrors



a) A concave, converging mirror



b) A convex, diverging mirror

Consider each of the three rays:

Incident Ray 1 travels from a point on the object parallel to the principal axis. Any ray that is parallel to the principal axis will reflect through the focal point on a converging mirror, or appear to have originated from the focal point on a diverging mirror.

Incident Ray 2 travels from a point on the object toward the focal point. Any ray that passes through the focal point on a converging mirror, or is directed at the focal point on a diverging mirror, will be reflected back parallel to the principal axis.

Incident Ray 3 travels from a point on the object toward the centre of curvature. Any ray that passes through the centre of curvature on a converging mirror, or is directed at the centre of curvature on a diverging mirror, will be reflected directly back along the incident path. At what incident angle must this light ray hit the mirror surface in order to be reflected straight back along the original path?

These three rays alone will allow you to predict and verify the location and characteristics of the image. Notice that some conventions are used when drawing these ray diagrams:

1. objects are often drawn as erect arrows
2. real rays are drawn as solid lines
3. virtual rays (that only appear to exist behind the mirror) are drawn as dashed lines

PHYSICS INSIGHT

All three incident rays obey the Law of Reflection. The resulting rules for drawing ray diagrams are just the application of geometry.

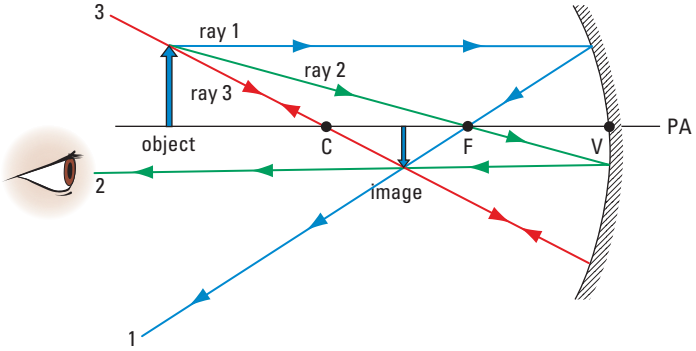
Figure 13.38 (a) shows that the converging mirror produces a real image that is inverted and diminished. Figure 13.38 (b) shows that the diverging mirror produces a virtual image that is erect and diminished. Why is one image real and the other virtual? For curved mirrors, a real image is formed where the reflected light rays converge or meet. At this location, a focussed image would appear on a sheet of paper or a screen if it were located in the exact location where the light rays meet. If the screen were to be moved slightly, the image would appear

blurred because the reflected rays would not be converging perfectly at the screen's new location. For the diverging mirror, the reflected rays appear to be originating from behind the mirror, but if a screen were located there, the incident light rays would not reach it (the rays would be blocked by the mirror).

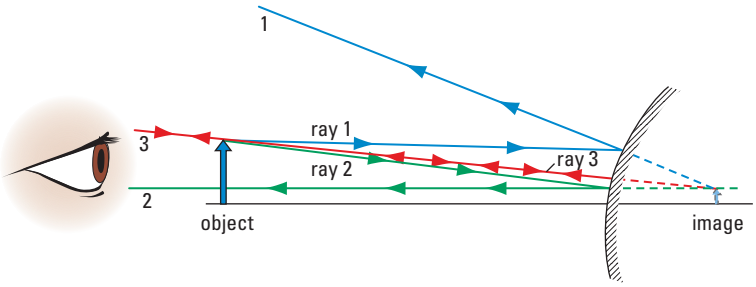
e WEB

To learn more about ray diagrams for curved mirrors and lenses, follow the links at www.pearsoned.ca/school/physicssource.

▼ **Figure 13.38** Steps for drawing a ray diagram in converging and diverging spherical mirrors



a) A concave, converging mirror

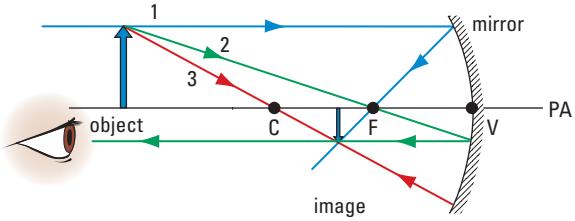


b) A convex, diverging mirror

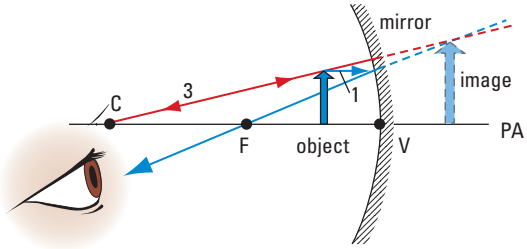
Characteristics of an Image in a Curved Mirror

If you look at the image of your face in a polished spoon and bring the spoon closer and closer to your nose, you will demonstrate that with curved mirrors, the object's distance from the mirror's vertex has an effect on the characteristics of the image produced. For example, what happens to an image as the object is brought closer to a converging mirror surface? In Figure 13.39(a), the object is located outside the centre of curvature, and a real, inverted, and diminished image appears. If the object is brought closer to the vertex of the mirror, such that it is inside the focal length, as in Figure 13.39(b), then the image becomes virtual, erect, and enlarged.

▼ **Figure 13.39** Object location affects image characteristics.



a) A converging mirror with object located outside C (real, inverted, diminished)



b) A converging mirror with object located inside F (virtual, erect, enlarged)

▼ **Table 13.3** Image Characteristics for Converging Mirrors

Object Position	Image Characteristic
distant	real, inverted, and diminished, close to F
outside centre of curvature	real, inverted, and diminished, between F and C
at the centre of curvature, C	real, inverted, and same size, at C
between focal point and centre of curvature	real, inverted, and enlarged, beyond C
at focal point, F	undefined (no image forms), at infinity
between focal point and vertex	virtual, erect, and enlarged, behind mirror

Table 13.3 summarizes the image characteristics for a concave, converging mirror. You can verify the characteristics by placing the concave side of a spoon in front of your nose and slowly moving it outward. Note that your image will disappear briefly just as the distance between your nose and the spoon reaches the focal point of the spoon. In a similar way, the image characteristics produced by a convex, diverging mirror can be investigated by using the other surface of the spoon.

13-4 QuickLab

Converging and Diverging Mirrors

Problem

How do image characteristics in converging and diverging mirrors change as you change the object distance?

Materials

polished spoon
drawing materials

Procedure

1. Place a polished metal spoon on your nose and slowly pull it away from your face while watching the image.
2. Complete ray diagrams for the image of your nose inside F, at F, at C, and at a distance, with respect to the spoon as a converging mirror. (Use a small upright arrow to represent your nose in the ray diagram.)
3. Reverse the spoon so that you are looking at the other side and move it away from your nose again.
4. Complete ray diagrams for the image of your nose inside F, at F, at C, and at a distance, with respect to the spoon as a diverging mirror. (Remember that a diverging mirror has a virtual focal length, so F and C are located on the opposite side of the spoon to your face.)

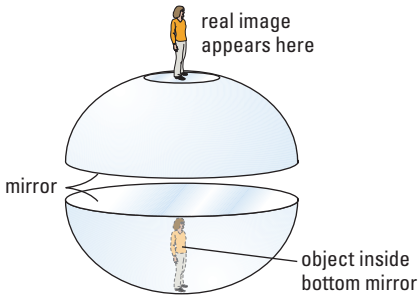
Questions

1. What happens to the image as the object is brought closer to the surface of a converging mirror?
2. What happens to the image as the object is brought closer to the surface of a diverging mirror?
3. What characteristics do all images formed in a diverging mirror share?
4. Your image disappears when your face is at the focal point of the mirror. Sketch a ray diagram for a converging mirror with the object located at the focal point to explain why an image should not appear when the object is located at the focal point.
5. Why is it not possible to put an object at F for a convex mirror?

MINDS ON Seeing Is Believing—Or Is It?

A parabolic mirror is shaped so that incident light rays that travel parallel to the principal axis will be reflected to a central point, or focus. Optical illusions can be produced by arranging two parabolic mirrors facing one another. Use a ray diagram to explain how a three-dimensional, real image, is produced in Figure 13.40.

Hint: The object is located at the focal point of the top mirror. Therefore, all rays that originate from the object will be reflected straight down from the top mirror. Assume the bottom mirror has the same focal length as the top mirror.



▲ **Figure 13.40** Two parabolic mirrors facing one another, with a hole cut around the vertex of one mirror

Equations for Curved Mirrors

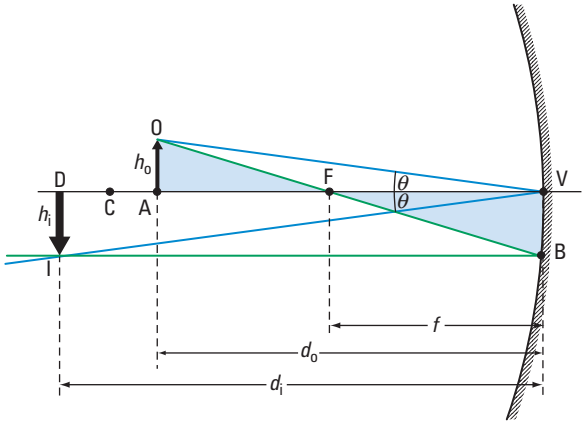
The general rules for drawing ray diagrams of curved mirrors, in combination with the law of reflection, allow us to generate several equations for use with curved mirrors. These equations can be used to determine the characteristics of the image.

In any ray diagram, two rays can be used to determine the image characteristics. In Figure 13.41, there are two similar triangles (AOV, above, and DIV, below). Both triangles have an identical angle (θ) and right angles at the principal axis. Thus,

$$\frac{\text{DI}}{\text{AO}} = \frac{\text{DV}}{\text{AV}}$$

This translates into $\frac{h_i}{h_o} = \frac{d_i}{d_o}$ where

h_o is the height of the object,
h_i is the height of the image,
d_o is the distance between the mirror vertex and the object, and
d_i is the distance between the mirror vertex and the image.



▲ **Figure 13.41** Triangles AOV and DIV are similar triangles; triangles FVB and FAO are also similar triangles.

When we use the ray OFB, the triangles FVB and FAO (shaded light blue) are also similar. Therefore,

$$\frac{\text{AO}}{\text{VB}} = \frac{\text{AF}}{\text{VF}}$$

Since

- AO $= h_o$
- VB $= h_i$
- AF $= d_o - f$
- VF $= f$

We can write this relationship as: $\frac{h_o}{h_i} = \frac{d_o - f}{f}$

Since $\frac{h_i}{h_o} = \frac{d_i}{d_o}$ the inverse is also true: $\frac{h_o}{h_i} = \frac{d_o}{d_i}$

Combining the equations gives: $\frac{d_o}{d_i} = \frac{d_o - f}{f}$

Dividing both sides by d_o and rearranging: $\frac{\cancel{d_o}}{d_i \cancel{d_o}} = \frac{\cancel{d_o}}{\cancel{d_o} f} - \frac{1}{d_o}$

We obtain this equation: $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$

mirror equation: the equation that relates the focal length of a curved mirror to the image and object distances

This is the **mirror equation**, which relates the focal length of a curved mirror to the image and object distances.

Sign Conventions for Use with the Mirror Equation

As we have seen previously, there are real and virtual images, which can form either in front of or behind the curved mirror. When using the mirror equation, it is therefore necessary to follow a sign convention, which can distinguish the type of image formed.

- Real objects and images have positive distances (measured from vertex).
- Virtual objects and images have negative distances (measured from vertex).
- Erect images and objects have a positive height.
- Inverted images and objects have a negative height.
- Converging mirrors have a real principal focal point and the focal length is positive.
- Diverging mirrors have a virtual principal focal point and the focal length is negative.

With this sign convention, a real image formed by a converging mirror will have a negative height (inverted attitude) while the object height is positive (erect attitude). Both the object and image distances will be positive. Magnification (m) is the ratio of the image height to the object height. A negative sign must be added to the equation for magnification to agree with the sign convention above.

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

An erect image has a positive magnification and an inverted image has a negative magnification.

Concept Check

1. If the object distance is extremely large, approaching infinity, $\frac{1}{d_o}$ becomes zero. Based on the mirror equation, where will the image form in relation to the focal length of the mirror?
2. For a plane, flat mirror, $\frac{1}{f}$ approaches zero. Based on the mirror equation, where will the image form in relation to the object?

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Using a Converging Mirror to Heat Water (Determining the Focal Length of a Converging Mirror)

Recognize a Need

A converging mirror can be used to focus the radiant energy of the Sun onto a specific point to capture energy, to heat water, or to generate electrical energy using a photovoltaic cell.

The Problem

Design an efficient apparatus that uses radiation to heat water.

Criterion for Success

Observing the maximum increase in water temperature in a given time period.

Brainstorm Ideas

To design an efficient water heater that uses sunlight for energy, you will need to consider the following questions:

- Where would a water tank be placed in relation to a converging mirror in order to maximize the amount of radiation that it could absorb?
- What colour should the water tank be?
- What effect will the size of the mirror have on the water temperature?
- What positive and negative effects would result from insulating the water tank?

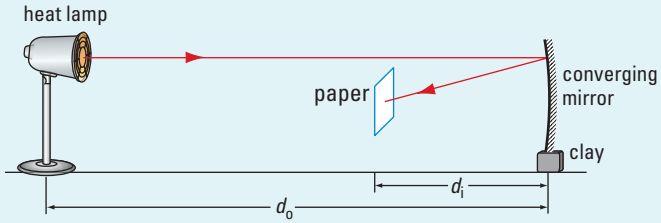
Build a Prototype

Construct a miniature version of your water heater using a 50-mL volumetric flask, a thermometer, and a converging mirror mounted on a base of clay.

Test and Evaluate

Determine the focal length of the converging mirror using a heat lamp, a metre-stick, and a sheet of paper (Figure 13.42). Recall that rays that travel parallel to the principal axis will be reflected back through the focal point.

1. Place the heat lamp a great distance away so that most of the incident rays travel parallel to the principal axis. Adjust the position of the paper until the light is focussed into a small region. Be careful not to block the light from reaching the mirror. You may need to adjust the position of the mirror to avoid this — try tilting it slightly downward and turning the room lights off to see the image clearly.
2. Record the distance between the paper and the vertex of the mirror. This is the approximate focal length of the mirror and it is also the image distance.
3. Measure the distance between the lamp and the mirror. This is the object distance. Using the mirror equation, with the image and object distances, calculate and verify the approximate focal length of the mirror.



▲ **Figure 13.42** Locating the focal point

4. Using the heat lamp in place of sunlight, measure the increase in water temperature for a given time period when the water tank is located beyond the focal point, at the focal point, and inside the focal point of the mirror.
5. Determine which position results in the greatest increase in water temperature and explain why.

Communicate

Using presentation software, create a brochure that outlines the basic operating principles of your water heater and explains the role of radiant energy in its operation.

Example 13.2

An object is located 20.0 cm from a converging mirror that has a focal length of 15.0 cm.

(a) Where will the image form relative to the mirror vertex?

(b) If the object is 5.00 cm high, determine the attitude, height, and magnification of the image.

Given

$d_o = +20.0$ cm

$f = +15.0$ cm (converging mirror has a positive focal length)

$h_o = +5.00$ cm (assume that the object is erect)

Required

image distance (d_i)

image height (h_i)

magnification (m)

Analysis and Solution

(a) To locate the image, use the relationship between focal length and object distance, the mirror equation:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$$

Now, solve for d_i:

$$\frac{1}{d_i} = \frac{1}{+15.0 \text{ cm}} - \frac{1}{+20.0 \text{ cm}}$$

$$d_i = +60.0 \text{ cm}$$

or

$$d_i = \frac{d_o f}{d_o - f}$$

$$d_i = \frac{(+20.0 \text{ cm})(+15.0 \text{ cm})}{(+20.0 \text{ cm}) - (+15.0 \text{ cm})}$$

$$d_i = +60.0 \text{ cm}$$

(b) To determine the attitude, height, and magnification, use the equation for magnification:

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

Now, solve for m:

$$m = -\frac{60.0 \text{ cm}}{20.0 \text{ cm}} = -3.0 \times$$

Practice Problems

1. A diverging mirror of focal length 10.0 cm produces an image of an object located 20.0 cm from the mirror. Determine the image distance and the magnification. Is the image real or virtual?
2. Determine the image distance, magnification, and attributes for the following:
   (a) a converging mirror with a focal length of 12.0 cm with an object 6.0 cm from the mirror
   (b) a diverging mirror of focal length 5.00 cm with an object 10.0 cm from the mirror
   (c) a diverging mirror of focal length 10.0 cm with an object 2.0 cm from the mirror
3. A 5.0-cm-high object is placed 2.0 cm in front of a converging mirror and the image is magnified $-4\times$. Where does the image form and what is the focal length of the mirror?
4. A 4.0-cm-high object is placed 15.0 cm from a concave mirror of focal length 5.0 cm. Determine the image characteristics using a ray diagram and the mirror equation.
5. Light from a distant planet is incident on a converging mirror. The image of the planet forms on a screen 45.0 cm from the vertex of the mirror. Find the focal length of the mirror and the image characteristics.

Answers

1. $d_i = -6.67$ cm; $m = 0.333\times$ virtual
2. (a) $d_i = -12$ cm; $m = 2.0\times$, virtual, erect, enlarged
   (b) $d_i = -3.33$ cm; $m = 0.333\times$, virtual, erect, diminished
   (c) $d_i = -1.7$ cm; $m = 0.83\times$, virtual, erect, diminished
3. $d_i = 8$ cm; $f = 1.6$ cm
4. $d_i = 7.5$ cm; $m = -0.5\times$; $h_i = -2.0$ cm; real, inverted, diminished
5. $f = 45.0$ cm; real, inverted, diminished

Then solve for h_i:

$$h_i = -\frac{d_i h_o}{d_o}$$

$$h_i = -\frac{(60.0\text{ cm})(+5.00\text{ cm})}{(+20.0\text{ cm})}$$

$$h_i = -15.0\text{ cm}$$

Paraphrase

(a) The real image forms 60.0 cm in front of the mirror vertex.
(b) It is inverted and magnified −3 times to a height of −15.0 cm.

13.3 Check and Reflect

Knowledge

1. Explain why the normal lines in Figure 13.27 are drawn in a variety of directions.
2. Create a concept map using ray diagram terminology including: principal axis, focal point, centre of curvature, and vertex.
3. Explain the difference between "specular" and "diffuse" reflection.
4. Compare "virtual" images with "real" images.
5. Compare "converging" and "diverging" mirrors.
6. Describe the path of the three rays that can be used to determine the characteristics of an image formed in a curved mirror.
7. Why does a diverging, convex mirror have a "virtual" focal point and not a "real" focal point?

Applications

8. An object 4.0 cm high is located 10.0 cm in front of a concave mirror. If the image produced is 5.0 cm high, what is the focal length of the mirror?
9. Draw a ray diagram for a converging mirror and determine the image characteristics when the object is located at:
   (a) 2.0 f (b) 0.50 f (c) 3.0 f
10. Draw a ray diagram for a diverging mirror and determine the image characteristics when the object is located at:
    (a) 0.50 f (b) 1.0 f (c) 1.5 f
11. Some flashlights and headlights use concave mirrors to help generate a light beam. If the light source is positioned at the focal point of the mirror, would all the reflected rays travel outward, parallel to the principal axis? Explain your answer. Include a ray diagram.

Extensions

12. A reflecting telescope uses a curved mirror to produce the image at the eyepiece. Research the telescope's design and function. Sketch a ray diagram to explain how the converging mirror is used in the telescope design.

eTEST

To check your understanding of reflection in plane and curved mirrors, follow the eTest links at www.pearsoned.ca/school/physicssource.

13.4 Refraction

▲ **Figure 13.43** A paddle as it appears partially submerged in water

refraction: a change in the direction of a light wave due to a change in its speed as it passes from one medium to another

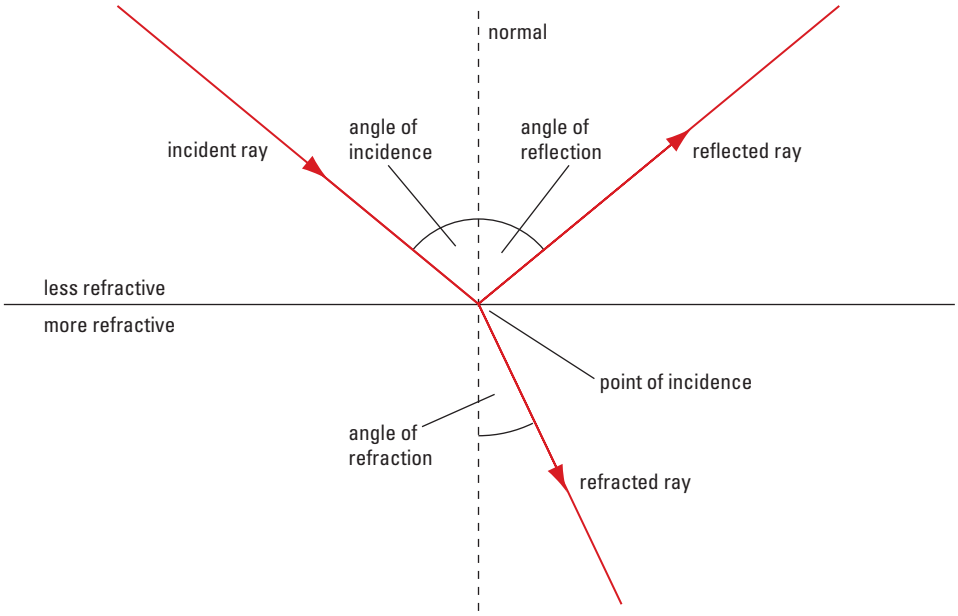
refractive index: a ratio comparing the speed of light in a vacuum to the measured speed of light in a given material

A paddle appears bent when you put it in water (Figure 13.43); the Sun changes shape when it sets; a rainbow appears when it rains; and a mirage occurs over the hot desert sand, or even over a hot Alberta highway during the day. These are all visual effects created by **refraction**, a change in the direction of a light wave due to a change in its speed as it passes from one medium to another.

When light rays pass at an angle from air to water, they immediately change direction. However, not all of the light will be refracted. Light rays are **partially reflected** and **partially refracted** when they pass from one medium to the next. Figure 13.44 illustrates this phenomenon.

The process of refraction is described by an **incident ray** and a **refracted ray**. The angle between the normal line (drawn perpendicular to the medium interface) and the incident ray is called the **angle of incidence**. The angle between the normal line and the refracted ray is called the **angle of refraction**. When the light ray passes from air to water, it is bent or refracted toward the normal line. And conversely, if a light ray travels from water into air, it is bent away from the normal line. The bending of the light ray depends on the **refractive index** of the medium in which the light travels.

The refractive index of a medium is related to the effect on the speed of light when it travels within that medium. A vacuum does not impede or slow down light travelling through it and therefore, the speed of light (c) is defined as its speed in a vacuum. Air slows the light down a small amount and thus has a slightly greater refractive index than a vacuum. Water slows the light down to a greater extent and has a greater refractive index than air. This retarding effect was observed in Fizeau's experiment on the speed of light in water (page 649). The amount of refraction is related to the magnitude of the change in the speed of light as it passes from one medium to another; the greater the change in speed, the greater the amount of refraction.



▲ **Figure 13.44** Ray diagram of partial reflection and partial refraction

Mathematically, the refractive index of a medium (n) can be described as a ratio that compares the speed of light in a vacuum (c) to the measured speed of light in the medium (v).

$$n = \frac{c}{v}$$

Table 13.4 lists the refractive indexes for some common substances. Since the speed of light in air is very close to the speed of light in a vacuum, the refractive indexes for a vacuum and for air are considered to be the same.

The following general rules are based on refractive indexes:

- When light passes from a medium with a high refractive index to one with a low refractive index, it is refracted away from the normal line.
- When light passes from a medium with a low refractive index to one with a high refractive index, it is refracted toward the normal line.

▼ Table 13.4 Absolute Refractive Indexes (for Sodium Yellow Light, $\lambda = 589$ nm)

Medium	Index of Refraction
vacuum	1.0000
air	1.0003
ice	1.31
water	1.33
ethanol	1.37
glycerin	1.47
quartz glass	1.47
crown glass	1.52
light flint glass	1.58
Lucite (plexiglass)	1.52
ruby	1.54
zircon	1.92
diamond	2.42

PHYSICS INSIGHT

On passing through a medium, each wavelength of EMR has a unique refractive index. For this reason, Absolute Refractive Indexes must be quoted for a specific wavelength, as in Table 13.4.

Snell's Law of Refraction

Although the phenomenon of refraction had been observed for centuries, it was not until 1621 that the Dutch mathematician, Willebrord Snell (1580–1626), identified the exact relationship between the angle of incidence and the angle of refraction. **Snell's Law** states that:

$$\frac{\sin \theta_i}{\sin \theta_r} = \text{a constant}$$

Snell's Law: For any angle of incidence greater than zero, the ratio $\sin \theta_i / \sin \theta_r$ is a constant for any light ray passing through the boundary between two media.

This relationship indicates that for any angle of incidence greater than zero, the ratio $\sin \theta_i$ / $\sin \theta_r$ will be constant for any light ray that passes through the boundary between the two media. In the case of an air-water interface, the constant is 1.33, which corresponds to the refractive index of water. In fact, for any ray that passes from air (θ_{air}) into a second medium (θ_r, refractive index n), Snell's Law may also be written in a simple form as:

$$\frac{\sin \theta_{air}}{\sin \theta_r} = n$$

As long as the first medium is air, the Snell's constant and the index of refraction for the second medium are one and the same thing.

If the first medium is not air, then the general form of Snell's Law applies. In the general form, the angle of incidence (θ_i) is replaced with θ_1 and the angle of refraction (θ_r) is replaced with θ_2. The index of refraction for the first medium is denoted as n_1 and the index of refraction

***info* BIT**

A mirage (derived from the Latin term "mirari," meaning "to be astonished") is a naturally occurring phenomenon caused by refraction. Often, mirages appear as large bodies of water on hot desert sand, or small puddles on highways. What appears as water is actually an image of the sky being refracted back up from the hot air just above the road surface.

▲ Figure 13.45

eSIM

Find out more about refraction through the use of simulations. Follow the eSIM links at www.pearsoned.ca/school/physicssource.

for the second medium is denoted as n_2. In all cases, the subscript "1" refers to the incident medium and the subscript "2" is reserved for the refracting medium. The general form of Snell's Law is written as:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

The general form of Snell's Law applies in all cases, regardless of the indexes of refraction of the media and/or the direction in which the light travels. Compare the general form with the simple form above. If the first medium is air, or a vacuum, so that n_1 is 1.00, substituting this value into the general form results in the simple form of Snell's Law.

Example 13.3

Yellow light travels from water into crown glass. The light rays are incident on the crown glass at an angle of 35°. Calculate the angle of refraction as the light enters the crown glass.

Given

$\theta_1 = 35°$

Required

the angle of refraction (θ_2)

Analysis and Solution

From Table 13.4,

- Index of refraction of water, the first medium, is $n_1 = 1.33$
- Index of refraction of crown glass, the second medium, is $n_2 = 1.52$

Therefore, the general form of Snell's Law applies.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2}$$

$$\theta_2 = \sin^{-1}\left(\frac{(1.33)(\sin 35°)}{1.52}\right)$$

$$\theta_2 = 30°$$

Paraphrase

The angle of refraction for the light travelling from water into crown glass is 30°, when the angle of incidence is 35°.

Practice Problems

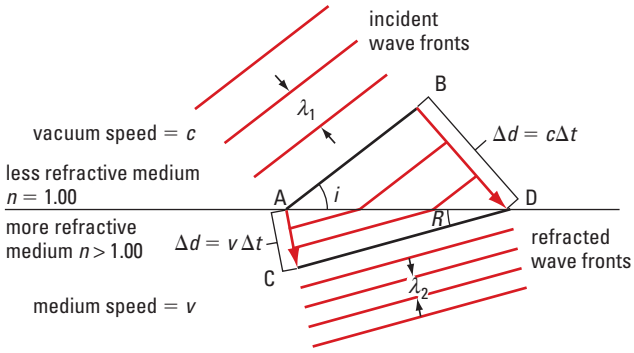
1. Light passes from a diamond into air. The angle of refraction as the light emerges from the diamond is 25°. What was the angle of incidence?
2. Light travelling from air into a transparent material is incident at an angle of 20° and refracted at an angle of 17°. Determine the index of refraction for the transparent material.
3. A ray of light passes from air into ruby at an incident angle of 15°. Calculate the angle of refraction.
4. A ray of light, travelling in air, is incident on an unknown sample at an angle of 20°. If the angle of refraction is 15°, determine the index of refraction for the unknown sample.

Answers

1. 10°
2. 1.2
3. 9.7°
4. 1.3

Snell's Law, Refraction, and Wavelength

Can we explain the phenomenon of refraction, and by association, Snell's Law, by considering light as a wave? Recall that the wave model describes light as a stream of transverse waves radiating outward from a source. Let us assume that the light waves are indeed transverse waves of electromagnetic radiation. As each wave front moves from one medium to the next the wavelength changes, as illustrated by Figure 13.46, but there is *no change* in frequency. In other words, the wave fronts do not "pile up" at the boundary between the two media. The number of waves arriving at the boundary is equal to the number of waves leaving the boundary for any given time interval, so the incident and refracted waves have the same frequency. However, the wavelength changes at the boundary. According to the universal wave equation ($v = f\lambda$), if the wavelength changes and the frequency remains constant, then the speed must change as well. To visualize this, consider light waves travelling from air into water as illustrated in Figure 13.46:



▲ **Figure 13.46** Wave fronts are refracted as they pass from air into water.

The wavelength in air is given by $\lambda_1 = v_1/f$;

The wavelength in water is given by $\lambda_2 = v_2/f$.

Since λ_1 is greater than λ_2, v_1 will be greater than v_2. This means the wave fronts in air travel faster than they do in water, as illustrated in Figure 13.46 and by Fizeau's experiment to measure the speed of light in water, page 649.

An enlarged view of two wave fronts, as shown in Figure 13.47, reveals another relationship. When we use similar triangles, the angle of incidence, θ_1 and the angle of refraction, θ_2 are shown within the coloured right triangles and they share the same hypotenuse, x.

Therefore, the trigonometric ratio for the sine of an angle when applied to each triangle gives:

$$\sin\theta_1 = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{\lambda_1}{x}$$

$$\sin\theta_2 = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{\lambda_2}{x}$$

Since

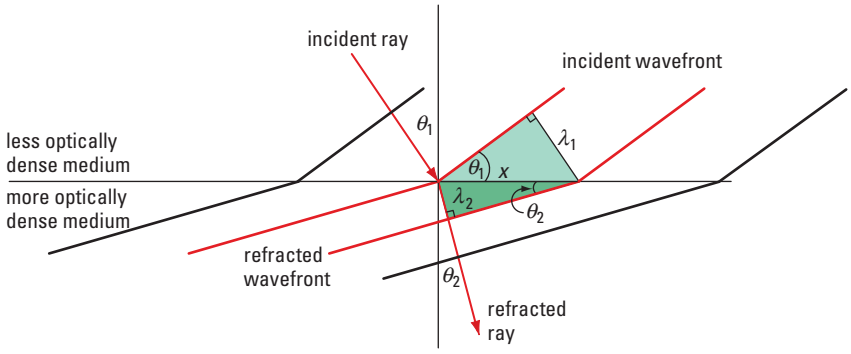
$$x = \frac{\lambda_1}{\sin\theta_1} \text{ and also } x = \frac{\lambda_2}{\sin\theta_2}$$

therefore

$$\frac{\lambda_1}{\sin\theta_1} = \frac{\lambda_2}{\sin\theta_2}$$

This equation can also be written as:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\lambda_1}{\lambda_2}$$



▲ **Figure 13.47** Enlarged view of two wave fronts

When the universal wave equation is used, the wavelength can also be written in terms of the wave speed as follows.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\frac{v_1}{f}}{\frac{v_2}{f}}$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

Therefore, Snell's Law can be expanded to read:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

By measuring the incident and refracted angles, velocity, and wavelength, this relationship can be tested.

Example 13.4

A ray of yellow light with a wavelength of 570 nm travels from air into diamond at an angle of 30°. Determine the following:
(a) the speed of light in the diamond
(b) the wavelength of the light as it travels in the diamond

Given

$\lambda_1 = 5.70 \times 10^{-7}$ m

Required

the speed of light in diamond (v_2)
the wavelength of light travelling in diamond (θ_2)

Analysis and Solution

v_1, the speed of light in air = 3.00×10^8 m/s

From Table 13.4,

- Index of refraction of air, the first medium, is $n_1 = 1.00$
- Index of refraction of diamond, the second medium, is $n_2 = 2.42$

The general form of Snell's Law applies: $\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$

Therefore,

$$v_2 = \frac{n_1 v_1}{n_2} \qquad \lambda_2 = \frac{n_1 \lambda_1}{n_2}$$

$v_2 = 1.24 \times 10^8$ m/s $\qquad$ $\lambda_2 = 2.36 \times 10^{-9}$ m *or* 236 nm

Paraphrase

(a) The speed of light in the diamond is 1.24×10^8 m/s.
(b) The wavelength of light in the diamond is 236 nm.

Practice Problems

1. Determine the speed of light in the following materials:
   (a) water
   (b) ethanol
   (c) ruby
   (d) crown glass
2. Light with a wavelength of 737 nm enters quartz glass at an angle of 25.0°. Determine the angle of refraction and the wavelength of the light in the quartz glass.
3. Light enters an unknown crystal from air with a wavelength of 500 nm. If the wavelength of the light in the crystal is found to be 450 nm, what is the refractive index of the crystal?

Answers

1. (a) 2.26×10^8 m/s
   (b) 2.19×10^8 m/s
   (c) 1.95×10^8 m/s
   (d) 1.97×10^8 m/s
2. 16.7°, 501 nm
3. 1.11

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Determining the Refractive Index of a Variety of Materials

In this experiment, known values of the refractive indexes of water and ethanol are verified.

Question

What are the refractive indexes of water and alcohol (ethanol)?

Variables

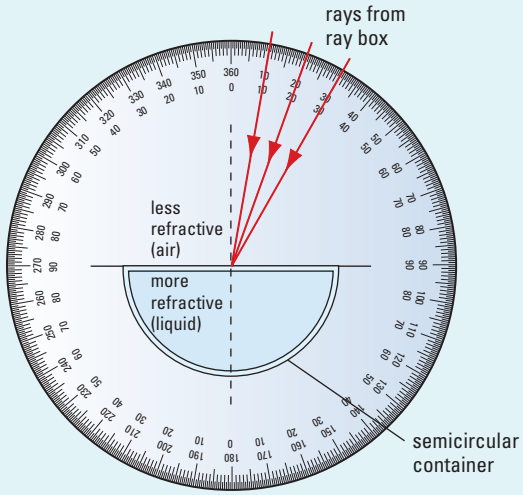
Manipulated variable: angle of incidence
Responding variable: angle of refraction
Controlled variables: refracting substance, wavelength of light

Materials and Equipment

polar coordinate paper
graphing paper
water
ethanol
single-slit ray box or laser
semicircular plastic dish

Procedure

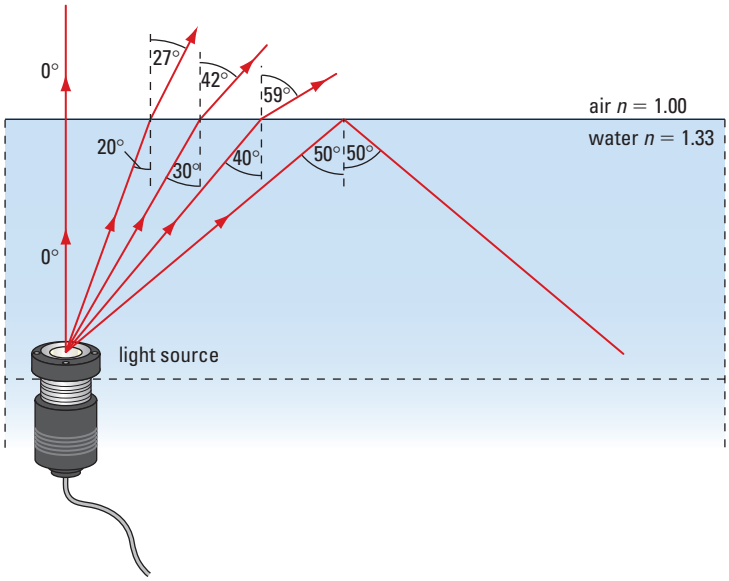
1. Design a data table or spreadsheet with the headings: angle of incidence (i), angle of refraction (r), sin angle of incidence (sin i), sin angle of refraction (sin r), and ratio sin i / sin r.
2. Fill the semicircular dish with water and place it on the polar coordinate paper such that the 0–180° line is perpendicular to the centre of the flat side of the dish. This will make the 0–180° line the normal line (Figure 13.48).
3. Direct a single ray of light along the normal line (0°). Record the angle of refraction. (This should be zero if the apparatus is set up correctly.)
4. Record the angles of refraction for 10° to 70°, increasing the angle by 10° for each step.
5. Complete the data table or spreadsheet calculations and plot a graph of sin angle of incidence vs. sin angle of refraction. Calculate the slope of this graph.
6. Repeat steps 2 to 5 using ethanol instead of water in the semicircular dish.



▲ **Figure 13.48** Semicircular dish on polar coordinate paper with several incident ray angles shown

Analysis

1. (a) What is the value of the slope for the graph when water was used as the refracting substance?
   (b) What is the value of the slope when ethanol was used as the refracting substance?
2. According to your slope calculations, which material, water or ethanol, has a higher index of refraction?
3. Calculate the percent error for each index of refraction using the absolute index of refraction given for each substance in Table 13.4.
4. Comment on the sources of error that could have occurred in this experiment.
5. Why is it important that the incident light ray contacts the semicircular dish at the centre?
6. Why is it important that a "semicircular" dish is used, instead of a rectangular dish?
7. Which material is more effective in changing the direction of light when light enters it?
8. Predict what would happen if the semicircular dish were replaced with a semicircular block of glass or Lucite®. If you have time, test your prediction.



▲ **Figure 13.49** Increasing the incident angle for light leaving a water-air interface leads to total internal reflection.

Total Internal Reflection

If you look down a long straight tube, you should be able to see what is at the other end. If the tube has a bend in it, a set of mirrors could be used to reflect the light through to your eye. This is how the periscope on a submarine works. But what if the tube has multiple bends in it? What could be done to ensure the light is able to travel through the entire length of the tube? Could you line the inside walls with mirrors and angle the light so that it reflects from side to side all along the tube, entering at one end and emerging at the opposite end?

In theory, this is exactly what happens in the optical fibres that facilitate the data and telephone communication of computer networks. The process is based on **total internal reflection.** Recall that when light travels from one medium to another, some of the light is partially reflected and some is partially refracted. When light travels from a medium with a high refractive index, like glass, to a medium with a low refractive index, like air, more of the light is reflected than it would be at an interface where its speed decreases.

total internal reflection: reflection of all incident light back into a medium of higher refractive index due to the inability to refract light beyond the maximum angle of 90°

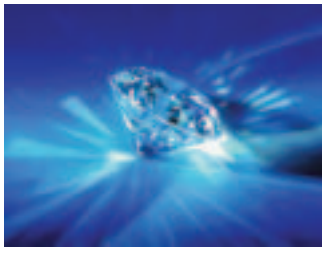
critical angle: for any two media, the size of the incident angle for which the angle of refraction is 90°

As illustrated by Figure 13.49, when light travels from the water with a high refractive index to the air with a low refractive index, it bends away from the normal line. As the angle of incidence is increased, the angle of refraction also increases, bending farther and farther from the normal line, and eventually reaching the maximum angle of 90°. Beyond this angle, refraction ceases and all incident light will be reflected back into the high-index medium (in this case, the water). Therefore, not all the light that approaches a water-air boundary will be refracted. The light approaching the boundary at large angles will be reflected back into the water. This is why underwater pool lights, for example, are not visible at all angles from above. At particular angles, they cannot be seen.

When the angle of refraction is 90°, the incident angle will have a value unique to the two media that form the interface. This unique angle of incidence is called the **critical angle.** For light travelling from a medium with a high refractive index to a medium with a low refractive index, the critical angle is determined by assuming that the angle of refraction is 90°.

info BIT

The sparkle and glitter associated with diamonds is caused by total internal reflection. The high index of refraction of the diamond and the skill of the jeweller in cutting and finishing are used to trap and focus light, which we observe as sparkles. Polar Bear Diamonds™, mined, cut, and polished in the Northwest Territories, are recognized for their quality worldwide.



▲ **Figure 13.50**

Concept Check

1. Is light refracted toward or away from the normal line when passing from a medium with a low refractive index like air, into a medium with a high refractive index like water?
2. Based on your answer above, can total internal reflection occur when light travels from a low-index medium like air, into a high-index medium like water? Explain why or why not.

Example 13.5

What is the critical angle for the quartz glass-air interface?

Given

The angle of refraction at the critical angle is defined to be $\theta_r = 90°$.

Required

the critical angle for this interface ($\theta_{critical}$)

Analysis and Solution

From Table 13.4,

- Index of refraction of air, the first medium, is $n_1 = 1.00$
- Index of refraction of quartz glass, the second medium, is $n_2 = 1.47$

Use the form of Snell's law for the critical angle:

$$n_2 \sin \theta_{critical} = n_1 \sin 90°$$

$$\sin \theta_{critical} = \frac{n_1 \sin 90°}{n_2}$$

$$\theta_{critical} = \sin^{-1}\left(\frac{n_1 \sin 90°}{n_2}\right)$$

$$\theta_{critical} = \sin^{-1}\left(\frac{1.00 \sin 90°}{1.47}\right)$$

$$\theta_{critical} = 42.9°$$

Paraphrase

Light at an incident angle of 42.9° or greater will be internally reflected at the quartz glass-air interface.

Practice Problem

1. Determine the critical angle for the following interfaces:
   (a) water and air
   (b) diamond and air
   (c) diamond and water

Answer

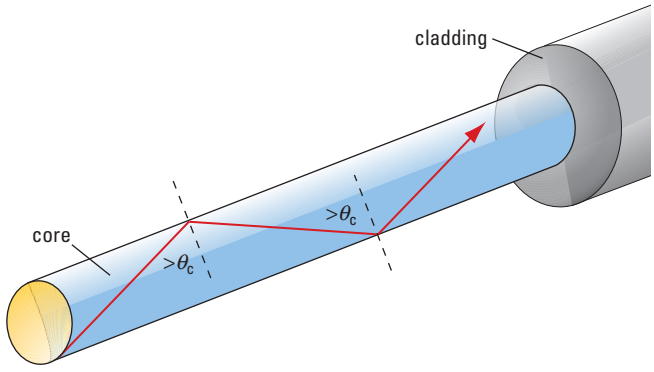
1. (a) 48.8°
   (b) 24.4°
   (c) 33.3°

e MATH

To investigate Snell's Law, refraction, and the concept of the critical angle, using a graphing calculator or a spreadsheet program, visit www.pearson.ca/school/physicssource.

Total internal reflection has many applications. Most notable are **optical fibres** (Figure 13.51). An optical fibre consists of a central core of glass with a refractive index of approximately 1.5, surrounded by a cladding material of a slightly lower refractive index. Such fibres are used to transmit data on computer and communication networks. The data are transmitted via the modulation of laser light travelling through a glass fibre, with virtually none of the energy loss associated with electrical transmission. Some of the advantages of fibre-optic networks include:

- economically less expensive than copper wire of equivalent length
- thinner, more flexible, and made of non-flammable materials
- able to handle a higher data-carrying capacity based on the fibre bundle diameter
- less signal degradation and interference between multiple signals on the same fibre as compared with copper networks
- the glass fibres are highly transparent so that repeaters (amplifiers) can be many kilometres apart, as opposed to coaxial cable repeaters that must be less than 1 km apart



▲ **Figure 13.51** An optical fibre showing cladding, core, axis, and critical angle

e WEB

To learn more about fibre optics including applications in audiovisual equipment and in nanotechnology, begin your search at www.pearsoned.ca/school/physicssource.

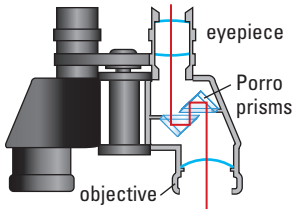
Fibre-optic systems also have drawbacks. The complex design of the fibres makes the fibre-optic system relatively expensive to set up and the fibres are also subject to wear and breakage.

info BIT

Buckyballs, also called C_{60} or buckminsterfullarenes, are soccer-ball-shaped molecules made of 60 linked carbon atoms. These carbon molecules may be formed into nanotubes to transmit data using light.

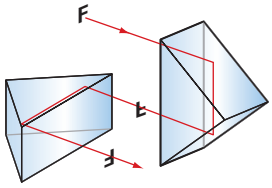
info BIT

Binoculars consist of two identical telescopes mounted side by side and aligned to point in the same direction. When the images from each side of the binoculars are viewed simultaneously, the user is able to sense depth and distance that is not possible with a single telescope view.



▲ **Figure 13.52**
The light path in binoculars

The Porro prisms in the binoculars use total internal reflection to direct light through the compact, short body of the binoculars with minimal absorption, producing a high-quality image.



▲ **Figure 13.53**
A double Porro prism

A double Porro-prism system is used in binoculars to reorient an inverted image while at the same time producing a longer, folded pathway for the light to travel between the objective lens and the eyepiece, producing a greater magnification.

13-7 Decision-Making Analysis

Fibre Optics: Endless Light

The Issue

The new knowledge society of today has emerged as a result of our ability to communicate and transmit data on a large scale. And to a very large extent, the infrastructure that supports our communication is based on the principles of total internal reflection and its application in fibre-optic systems. New and innovative advances are being made with fibre optics every day – from nanotechnology to entertainment services.

Background Information

The flexibility of fibre optics has allowed for applications in a variety of industries. For example, telephone, television, and data networks, originally all separate industries, are merging into one large application, which is supported by a fibre-optic backbone.

In medicine, applications include the use of a fibrescope to both illuminate internal organs and capture images of them. For example, to see inside the small intestine, an endoscope, a small, flexible bundle of fibres is inserted down the patient's throat and through the stomach. Once the fibres reach the small intestine, images can be transmitted through individual fibres while others are simultaneously used to illuminate the tissue. This application prevents the need for more-invasive, risky procedures that can leave the patient with a higher risk of infection and perhaps result in a prolonged hospital stay.

Other applications include mechanical imaging. For example, fibre-optic bundles can be used to inspect the interior of long pipes, vessels, and hard-to-reach locations, such as bore holes for oil and water wells, pipelines, and hazardous goods containers. With proper instrumentation devices attached, fibre-optic bundles can be used in dangerous conditions to identify gases, pressures, temperatures, and concentrations.

Nanotechnology is an emerging application for fibre optics. In this industry, new nanomaterials, such as C_{60} (buckyballs), are being investigated to expand the power and application of data transmission using light.

Analyze and Evaluate

1. Research applications of fibre optics using the Internet, research journals, and periodicals.
2. Group all the applications by industry and identify what you believe to be the most important applications in each industry.
3. For each of the most important applications, identify the social, political, economic, and environmental impact of the technology.
4. New applications of fibre optics are emerging in nanotechnology. Identify these applications and describe what technological advances could be expected as a result of merging nanotechnology with fibre-optic technology.
5. Prepare a multimedia presentation that demonstrates advances that have been made in a number of industries as a result of fibre-optic applications. Predict what future applications and social issues will evolve as new technologies begin to merge with fibre optics.

Prisms — Dispersion of White Light

Where have you seen a rainbow? Everyone has seen one in the sky, but what about in a diamond, or perhaps on the wall near a hanging crystal in a window. There are many items that produce a rainbow of colours, but all the rainbows have something in common. They all originate from white light.

The investigation of such effects was undertaken by Newton in 1666. He placed a transparent prism in a beam of sunlight passing through his window shutter at Cambridge University. On the opposite wall, an elongated band of colours appeared and he called this a **spectrum** (Figure 13.54). In this spectrum, Newton noted the colours red, orange, yellow, green, blue, indigo, and violet, in the order in which they appeared.

Newton set out to determine which of two things was true: either the colours of the spectrum are added to the white light by the prism, or the prism separates all the colours from the white light. To test this, Newton set up two prisms, the first one exposed to white light, producing a spectrum of colours (Figure 13.55(a)), and the second one, only exposed to the red (monochromatic) light coming from the first prism. The second prism did not produce any more colours; only the red light emerged. As a second test, Newton inverted the second prism and allowed the spectrum of colours from the first prism to enter it. The spectrum disappeared and only white light emerged from the second prism (Figure 13.55(b)).

Based on his observations, Newton concluded that white light is made up of all the colours in the spectrum and the prism was simply separating the colours from one another. The separation of white light into its components is called **dispersion.**

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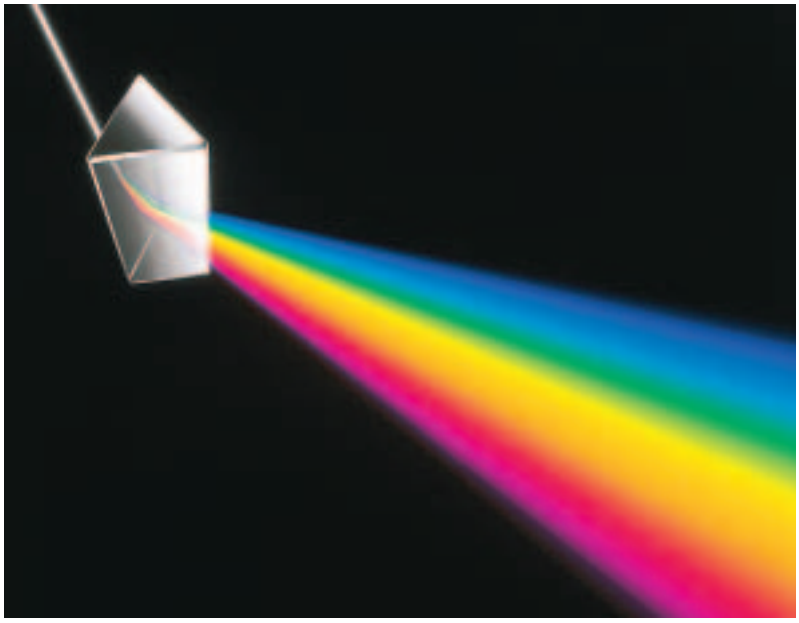
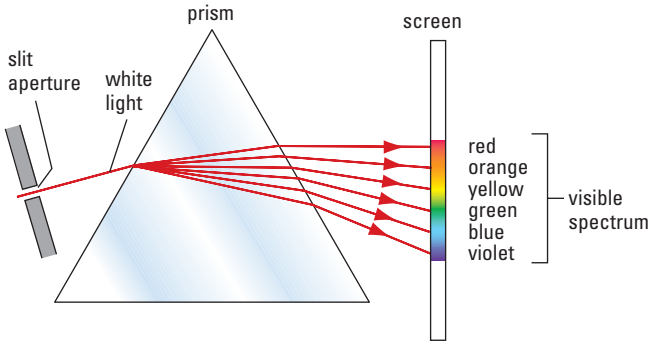
It may be that Newton noted seven colours in the spectrum, in part to go along with the views of society at that time: numerology regarded 7 as a "special" number. Six colours are more commonly used, as in Figure 13.55(a) and Table 13.5.

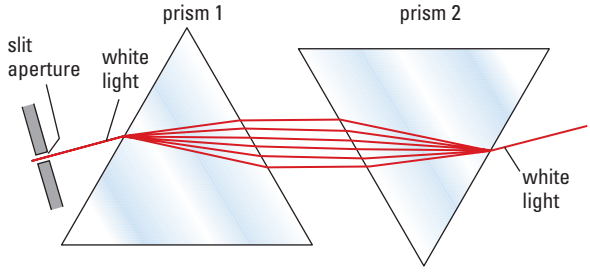
spectrum: the bands of colours making up white light; in order, red, orange, yellow, green, blue, violet

dispersion: separation of white light into its components

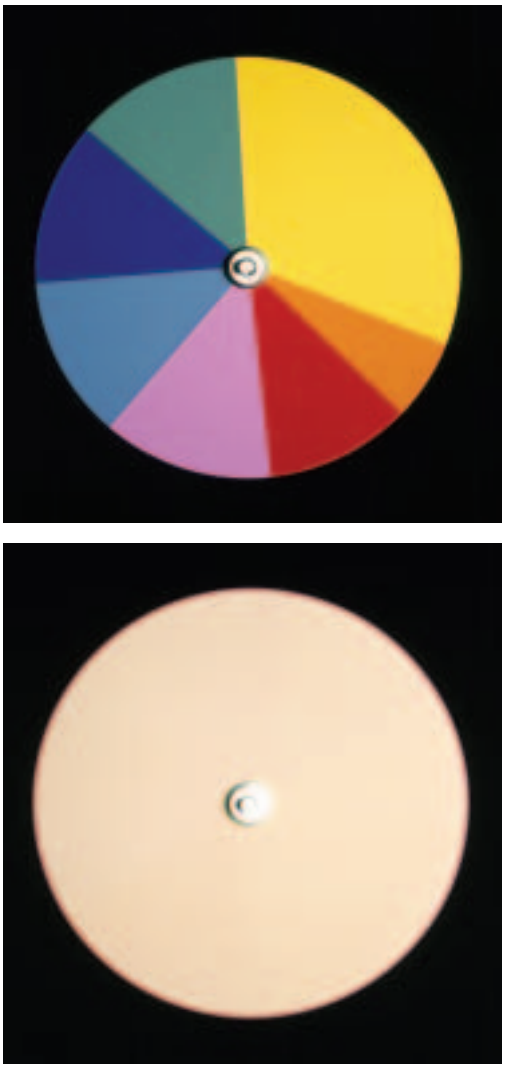


▲ **Figure 13.54** The complete spectrum produced by white light passing through a prism





▲ **Figure 13.55** (a) Dispersion of white light by a prism (b) Recomposition of white light using an inverted prism



▲ **Figure 13.56** Recomposition of the spectrum using a high-speed disc

The **recomposition** of the spectrum, therefore, should produce white light, as Newton was able to demonstrate in his second experiment (Figure 13.55(b)). Recomposition can also be demonstrated by painting all the colours of the spectrum in certain proportions on a disc and spinning the disc at a very high speed (Figure 13.56). At sufficient speed, the disc appears white.

Is dispersion consistent with the wave model of light? If we consider light as a wave, each of the colours in the spectrum has a unique wavelength, as listed in Table 13.5. As light enters a medium with a high refractive index, the wavelength is reduced but the frequency is unchanged. The speed of a wave is the product of its frequency and wavelength as described by the universal wave equation ($v = f\lambda$). Therefore, the light must slow down as it enters the high-index medium. Because the refractive index is related to the speed of a wave, it is therefore also related to the wavelength of the wave when the frequency is constant.

$$n = \frac{\lambda_o}{\lambda}$$

λ_o = wavelength in vacuum

λ = wavelength in medium

This relationship between refractive index and wavelength, for a constant frequency, means that the refractive index is different for each wavelength of light that passes through the same medium. Incident light with a smaller, shorter wavelength will slow down and refract to a greater extent than light with a larger, longer wavelength. As each wavelength of light refracts at a slightly different angle, the wavelengths will separate, producing a continuous spectrum. The wave model of light, therefore, is consistent with the phenomenon of dispersion.

eSIM

To learn more about the effects of prisms through the use of simulations, follow the eSim links at www.pearsoned.ca/school/physicssource.

▼ **Table 13.5** Wavelength of each colour in the spectrum

Colour	Wavelength λ (nm)
ultraviolet B	208-320
ultraviolet A	320-400
violet	400-450
blue	450-500
green	500-570
yellow	570-590
orange	590-610
red	610-750
infrared	>750

13-8 QuickLab

Dispersion Using a Prism

Problem

Is white light made up of all the colours we can see?

Materials

2 identical prisms
convex lens
intense light source (flashlight or white light ray box)
white paper

Procedure

1. Using one prism, observe the colour spectrum on a piece of white paper. A dark room and a very intense white light source will work best. The convex lens may be placed between the light source and prism to intensify the beam of white light if the spectrum is not immediately clear and visible.
2. Position the second prism in the spectrum produced by the first one. Rotate the second prism and position the white paper so that you can observe the light that emerges from the second prism.
3. Explore a variety of positions and orientations with both prisms.

Questions

1. What is the best way to make a colour spectrum using a single prism? Draw a picture showing the flashlight, prism, convex lens, paper, and the colour spectrum.
2. List the colours of the spectrum from most refracted to least refracted.
3. Compare the wavelengths of each colour to the amount of refraction observed. Describe the relationship between wavelength and amount of refraction.
4. Are the colours of the spectrum added to, or separated from, white light when white light passes through a prism? Support your answer with observations made using two prisms.
5. The spectrum produced by a prism is similar to that observed as a rainbow. Research and explore the similarities between the spectrum produced by a prism and that which is observed as a rainbow.

Thin Lenses

Projection systems connected with computers and movie players, and optical systems including microscopes and telescopes, use lenses that refract light in order to generate images. A typical thin lens is a circular piece of transparent material with a spherically shaped surface that refracts, or changes the direction of light that passes through it. The uniformly curved surface will refract light rays to varying extents depending on where they contact the lens. Rays that are incident near the edge of the lens will be refracted at larger angles than those that are incident near the centre, where the two faces of the lens are almost parallel.

For a **converging lens,** rays that travel parallel to the principal axis will be refracted inward, intersecting at the principal focus, F. For a **diverging lens**, rays that travel parallel to the principal axis will be refracted outward, appearing as though they have originated at a virtual principal focus, F. The distance from each lens to F is the focal length, f (Figure 13.57). Each type of lens has a secondary focus, F′ at a distance of f, on the opposite side of the lens. Each lens also has two centres of curvature (C and C′). The distance from a centre of curvature to the lens represents the radius of the sphere from which the lens surface is made.

PHYSICS INSIGHT

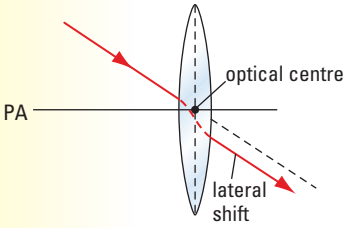
A converging lens has a convex surface while a diverging lens has concave surfaces. Other lenses, including those used in eyeglasses, can have both convex and concave surfaces; it is therefore more useful to refer to a lens by what it does rather than the types of surfaces that are found on it.

converging lens: a lens that refracts rays travelling parallel to the principal axis inward to intersect at the principal focus

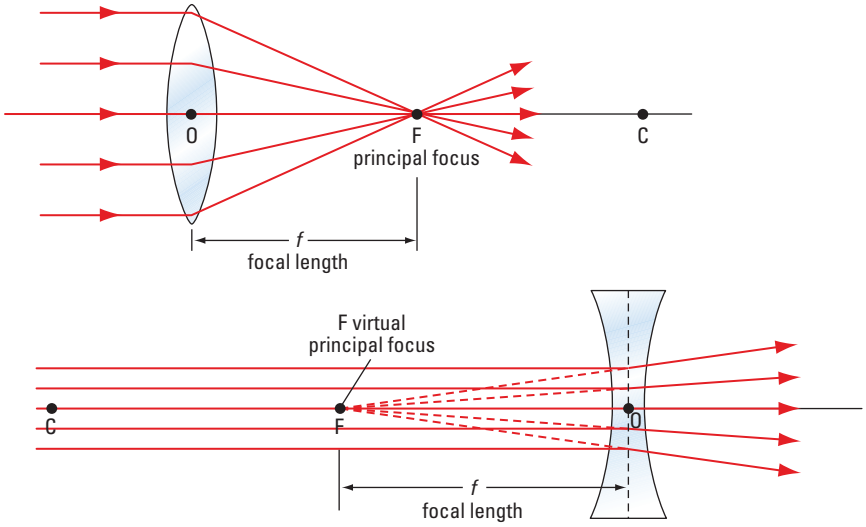
diverging lens: a lens that refracts rays travelling parallel to the principal axis outward to appear as though they have originated at a virtual principal focus

PHYSICS INSIGHT

A ray that travels through the optical centre is indeed refracted. This causes the refracted ray to emerge parallel to, but laterally shifted from, the incident ray. For a thin lens, this lateral shift is so small that it is assumed that the ray is not refracted.



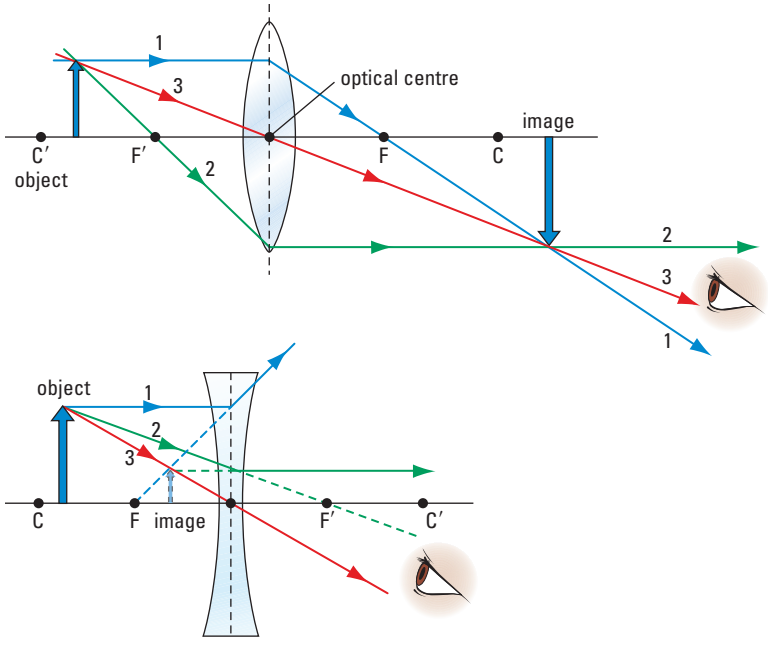
▲ **Figure 13.58**
Lateral shift



▲ **Figure 13.57** Converging and diverging lenses

Drawing Ray Diagrams for Thin Lenses

A ray diagram is a useful tool for predicting and understanding how images form as a result of light rays emerging from a curved lens. Ray diagrams for lenses are similar to the ray diagrams used with curved mirrors; only two rays are needed to predict the image location, and a third is used as verification (Figure 13.59).



▲ **Figure 13.59** Ray diagrams for (a) converging, and (b) diverging lenses

Ray 1 travels parallel to the principal axis and is refracted such that it emerges and passes through (or appears to have originated from) the principal focus, F.
Ray 2 travels through (or appears to have originated from) the secondary focus, F′, and is refracted such that it emerges and travels parallel to the principal axis.
Ray 3 travels straight through the optical centre of the lens and is not bent.

The ray diagram is not only used to identify the location of an image relative to the lens, but it can also illustrate the other three image attributes of type, attitude, and magnification, that have previously been described for curved mirrors. Relative to the object, the image produced by a curved lens can be real or virtual, inverted or erect, and enlarged or diminished.

Example 13.6

Draw a diagram to determine the image attributes for an object located at the following positions relative to a converging lens.

a) beyond the center of curvature C′ (or 2*f*)
b) at F′
c) between the lens and F′

Given

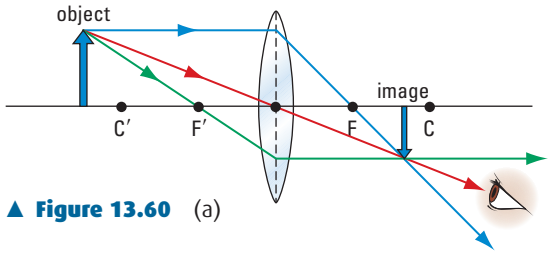
Object position relative to the converging lens

Required

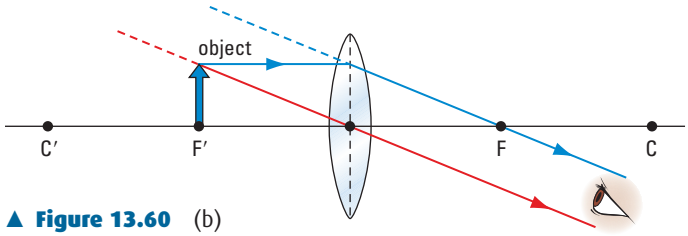
Ray diagram showing image location and attributes

Analysis and Solution

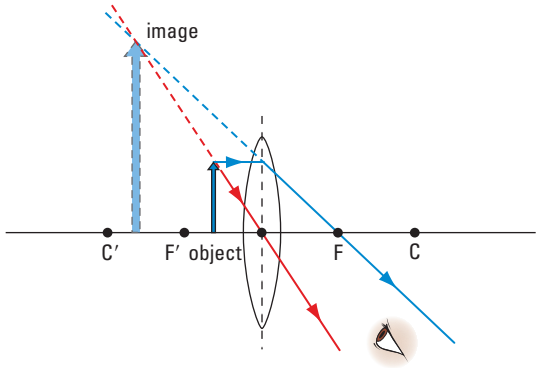
Construct a ray diagram and visually inspect the image location relative to the converging lens and the image attributes.



▲ **Figure 13.60** (a)



▲ **Figure 13.60** (b)



▲ **Figure 13.60** (c)

Paraphrase

(a) The image is located between F and C, and is real, inverted, and diminished.
(b) No image is formed.
(c) The image is located between F′ and C′, and is virtual, erect, and enlarged.

Practice Problem

1. Using a ray diagram, determine the image attributes for the following:
   (a) an object located between C′ and F′ relative to a converging lens
   (b) an object located between C′ and F′ relative to a diverging lens
   (c) an object located between F′ and a converging lens
   (d) an object located between F′ and a diverging lens

Answer

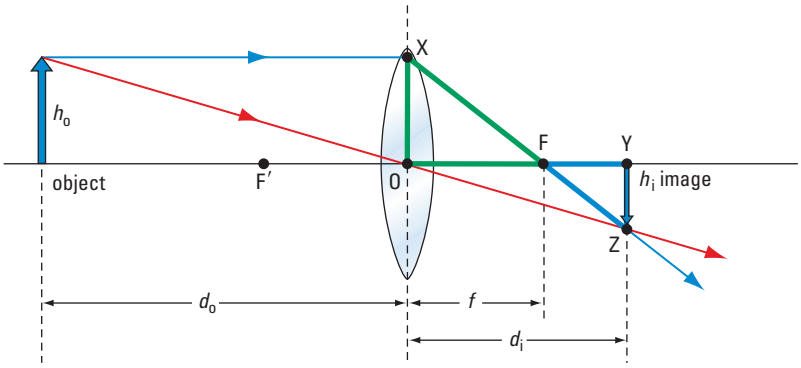
1. (a) Image is beyond C, real, inverted, and enlarged.
   (b) Image is between the lens and F, virtual, erect, and diminished.
   (c) Image is between F′ and C′, virtual, erect, and enlarged.
   (d) Image is between the lens and F′, virtual, erect, and diminished.

eWEB

To learn more about thin lenses, follow the links at www.pearsoned.ca/school/physicssource.

Equations for Thin Lenses

An equation relating object distance, image distance, and the focal length of a curved lens can be derived using an analysis nearly identical to that for curved mirrors. In Figure 13.61, the green triangle XOF and the blue triangle ZYF are similar. Therefore,



▲ **Figure 13.61** Thin lens ray diagram

$$\frac{OX}{OF} = \frac{YZ}{YF}$$

$$\frac{h_o}{f} = \frac{h_i}{d_i - f}$$

$$\frac{h_i}{h_o} = \frac{d_i - f}{f}$$

$$\frac{h_i}{h_o} = \frac{d_i}{d_o}$$

$$\frac{d_i}{d_o} = \frac{d_i - f}{f}$$

$$\frac{d_i}{d_o} = \frac{d_i}{f} - \frac{\cancel{f}}{\cancel{f}}$$

Dividing both sides by d_i, and simplifying, gives the **thin lens equation**.

$$\frac{\cancel{d_i}}{\cancel{d_i} d_o} = \frac{\cancel{d_i}}{\cancel{d_i} f} - \frac{1}{d_i}$$

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

thin lens equation: the equation that relates object distance, image distance, and focal length of a curved lens

Notice that this equation is identical to the mirror equation. A sign convention will be used here also, to distinguish between real and virtual distances as well as to identify erect and inverted images.

Sign Conventions for the Thin Lens Equation

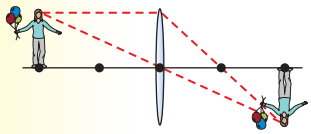
- All distance measurements are relative to the optical centre of the lens.
- Positive distances are used for real objects and images.
- Negative distances are used for virtual images.
- Positive image and object heights are upward relative to the principal axis.
- Negative image and object heights are downward relative to the principal axis.
- Converging lenses have a positive focal length.
- Diverging lenses have a negative focal length.

Results with a thin lens are similar to those with a curved mirror in that an erect image has a positive magnification and an inverted image has a negative magnification. Therefore, the same magnification equation that is used for curved mirrors is also used for thin lenses.

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

PHYSICS INSIGHT

Although a converging lens can cause an image to be vertically inverted, this does not mean that it will be horizontally inverted as well. In fact, if an object is located at the centre of curvature for a thin convex lens, the image will be vertically inverted, but not horizontally inverted.



▲ **Figure 13.62**
A vertically, but not horizontally, inverted object

Example 13.7

A 2.5-cm-high object is placed 10.0 cm from a diverging lens of focal length 5.0 cm. Determine the image distance, height, and attributes using the thin lens equation. Verify your answer with a ray diagram.

Given

$h_o = +2.5$ cm

$d_o = +10.0$ cm

$f = -5.0$ cm (The lens is a diverging lens.)

Required

image distance (d_i)

height (h_i)

image characteristics

Analysis and Solution

The thin lens equation can be used to determine the image distance, image height, and attributes. A ray diagram can verify the answer.

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \qquad \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} \qquad h_i = -\frac{d_i h_o}{d_o}$$

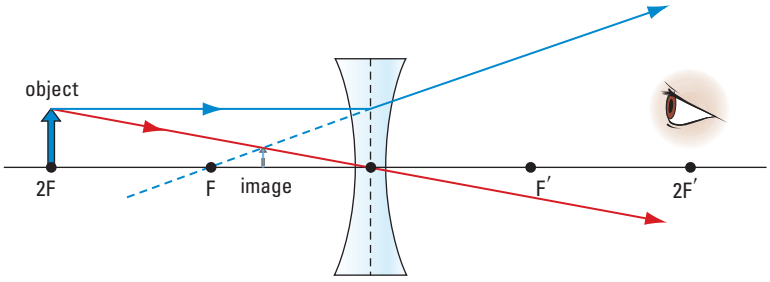
$$\frac{1}{d_i} = \frac{1}{-5.0\text{ cm}} - \frac{1}{+2.5\text{ cm}} \qquad h_i = -\frac{(-1.6667\text{ cm})(+2.5\text{ cm})}{+10.0\text{ cm}}$$

$$\frac{1}{d_i} = \frac{1}{-5.0\text{ cm}} - \frac{1}{+2.5\text{ cm}} \qquad h_i = +0.42\text{ cm}$$

$$\frac{1}{d_i} = -1.7\text{ cm}$$

Paraphrase

The image distance is −1.7 cm and height is +0.42 cm, indicating the image is virtual, erect, and diminished. The answers are verified by the ray diagram in Figure 13.63.



▲ **Figure 13.63**

Practice Problems

1. A 3.00-cm-high object is located 15.0 cm from a converging lens with a focal length of 10.0 cm.
   (a) How far is the image from the lens?
   (b) How high is the image?
   (c) Describe the image characteristics and verify them using a ray diagram.
2. A 10.0-cm-high candle is placed 100.0 cm from a diverging lens with a focal length of 25.0 cm. Determine the following using a ray diagram and the thin lens equation:
   (a) the image location from the lens
   (b) the image height
   (c) the type of image formed
3. A projector uses a converging lens to create a focussed image on a screen located 5.00 m away. The image is generated from a slide located 7.50 cm from the lens.
   (a) What is the focal length of the lens?
   (b) Determine the magnification of the image.

Answers

1. (a) $d_i = 30.0$ cm
   (b) $h_i = -6.00$ cm
   (c) image is real, inverted, enlarged
2. (a) $d_i = -20.0$ cm
   (b) $h_i = 2.00$ cm
   (c) image is virtual
3. (a) $f = 7.39$ cm
   (b) $m = -66.7$ X

13-9 Inquiry Lab

Required Skills
- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Comparing Keplerian and Galilean Telescopes

In this investigation the functional differences between a Keplerian telescope, with two converging lenses, and a Galilean telescope, with one converging lens and one diverging lens, are explored.

Question

What are the differences between Keplerian and Galilean telescopes?

Variables

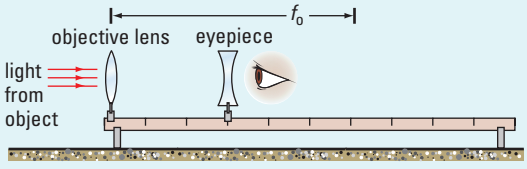
manipulated: type of lens used
responding: magnification of the image
controlled: focal length of double concave and double convex lenses

Materials and Equipment

- long focal length converging lens
- short focal length converging lens
- short focal length diverging lens
- lens holders
- optical bench for measuring distances
- lamp
- paper, ruler, pencil, and tape

Procedure for Galilean Telescope

1. Place the long focal length converging lens at one end of the optical bench. This will serve as the objective lens for both telescopes.
2. If the long focal length is unknown, place a lamp in front of the lens and measure the distance between the lamp and the lens. Next, slide a sheet of paper or screen along the optical bench until a bright spot appears (image of the lamp). Record the distance between the paper and the lens. Calculate the focal length of the objective lens using the lens equation, and image and object distances.
3. Place the short focal length diverging lens halfway between the converging lens and its principal focus as illustrated in Figure 13.64.

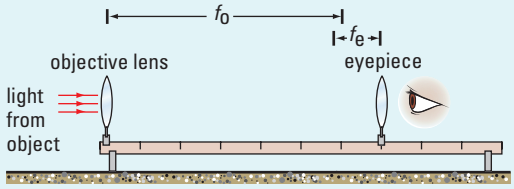


▲ **Figure 13.64** Galilean telescope

4. Draw a series of 5 vertical arrows, 1 cm apart, on a sheet of paper. Tape the sheet to a distant wall so that it will be visible in the telescope.
5. Look through the eyepiece with one eye and compare the image with the sheet seen with an unaided eye.
6. Estimate how many vertical arrows (viewed with the unaided eye) would fit in between two of the vertical arrows observed in the telescope. Record this as the estimated magnification.

Procedure for Keplerian Telescope

7. Remove the diverging lens from the optical bench.
8. If the focal length of the short focal length converging lens is not known, place a lamp in front of the lens and slide a sheet of paper or screen along the optical bench until a bright spot appears. Record the focal length for the short focal length lens.
9. Position the short focal length converging lens such that the distance between the two lenses is slightly less than the sum of the focal lengths, as shown in Figure 13.65.



▲ **Figure 13.65** Keplerian telescope

10. Estimate how many vertical arrows (viewed with the unaided eye) would fit in between two of the vertical arrows observed in the telescope. Record this as the estimated magnification.

Analysis

1. Prepare a table that compares the attitude, magnification, and brightness of the image in each telescope.
2. Complete a ray diagram to show how the image is formed in each telescope.
3. Suggest a different application for each telescope. Compare the telescopes' efficiency in looking at relatively close terrestrial objects, like mountains, or far away extraterrestrial objects, such as the Moon.

13.4 Check and Reflect

Knowledge

1. Is light bent toward or away from the normal line when it passes from a low-index medium to a high-index medium?
2. How is the index of refraction measured for a particular medium?
3. Construct a concept map using the following terms: incident ray, refracted ray, angle of incidence, angle of refraction, normal line.
4. What is the difference between the simple and general forms of Snell's Law?
5. Suggest an experimental design to determine the critical angle for an air-Lucite® boundary.
6. List five advantages of a fibre-optic network when compared to traditional electric networks used for data transmission.
7. How does a prism separate all the colours of white light?
8. Explain the effect of wavelength on the index of refraction for a particular medium, like glass. How does this lead to dispersion?

Applications

9. What is the speed of light in water ($n = 1.33$)?
10. A light ray is incident on a block of quartz glass ($n = 1.47$) at an angle of 35.0°. Determine the angle of refraction.
11. When a ray of light passes from water ($n = 1.33$) into a Lucite® block ($n = 1.52$) it is refracted at an angle of 28.0°. Determine the angle of incidence.
12. What is the critical angle for a Lucite®-air interface?
13. A light ray travelling in water approaches the water-air boundary at an angle of 50°. What happens to the light ray at the boundary?
14. Light with a wavelength of 540 nm enters a ruby crystal ($n = 1.54$) at an angle of 25.0°. Determine the angle of refraction and the wavelength of the light in the ruby.
15. Using ray diagrams, determine the image attributes for an object located at the following positions relative to a converging lens:
    (a) at C′
    (b) between 2F′ and F′
    (c) at F′
16. A camera with a converging lens ($f = 4.50$ cm) is used to take a picture of a 25.0-m-high tree that is 50.0 m from the camera. How tall is the image? Is it erect or inverted?
17. Red light of 700 nm and blue light of 475 nm are both incident on a Lucite® block. Which colour will be refracted to a greater extent?
18. The focal length of the converging lens in a computer projector is 8.00 cm. An LCD panel positioned inside the projector serves as the object for the lens.
    (a) If the LCD panel is located 8.10 cm from the lens inside the projector, how far away should the screen be placed so that a clear image is produced?
    (b) If the LCD panel is 1.75 cm high, how large is the image on the screen?
    (c) If the screen is moved 3.0 m closer to the projector, how far must the object now be from the lens in order to generate a focussed image?

Extensions

19. Explain why jewellery crystals, such as diamonds, sparkle.
20. Explain why you can start a fire with a magnifying glass.
21. If a diver is underwater and looks up, a circular "hole" appears on the surface of the water directly above the diver. Other than this hole, the surface appears as a mirror. Explain how this happens.

eTEST

To check your understanding of refraction, fibre optics, dispersion, and lenses, follow the eTest links at www.pearsoned.ca/school/physicssource.

13.5 Diffraction and Interference

▲ **Figure 13.66**
Christiaan Huygens

In section 8.3 you learned that there are many forms of interference patterns produced by mechanical waves that travel in a medium like water. And more importantly, you learned that the interference pattern contains information about the properties of the waves that created the pattern. In this section, we will investigate interference patterns produced by electromagnetic radiation and analyze the patterns to further our understanding of the wave model of light.

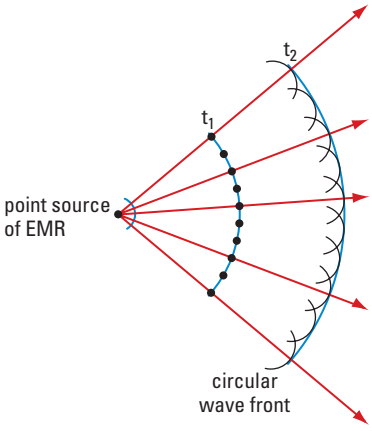
Huygens' Principle

Robert Hooke proposed the Wave Model of Light in his *Micrographica* of 1665. The first major improvement to this model was made by Christiaan Huygens (Figure 13.66), twenty years later. A Dutch physicist, Huygens contributed to the study of astronomy by advancing techniques in lens grinding and by discovering Saturn's rings and its largest satellite, Titan. He is also credited with producing the pendulum clock, originally proposed by Galileo. With regard to wave theory, Huygens described an elegant, conceptual model that predicted the motion of a wave front. This model is known as **Huygens' Principle.**

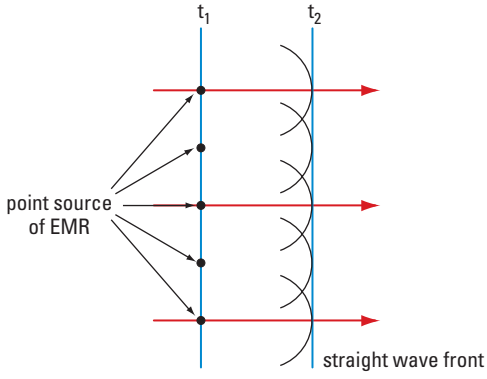
Huygens' Principle: a model of wave theory, which predicted the motion of a wave front as being many small point sources propagating outward in a concentric circle at the same speed as the wave itself

A wave front consists of many small point sources of tiny secondary waves, called wavelets, which propagate outward in a concentric circle at the same speed as the wave itself. The line tangent to all the wavelets constitutes the wave front.

To visualize Huygens' Principle, consider a point source of light that emits electromagnetic waves outward, in a concentric circle. At an instant in time, the wave front will form the line t_1. According to Huygens' Principle, all the points along line t_1 become secondary sources, producing wavelets that radiate outward to form the wave front at a future time t_2. Line t_2 is the tangent to all the wavelets that make up the wave front a short time later (Figure 13.67). The same analysis can be performed on a straight wave front, as shown in Figure 13.68.



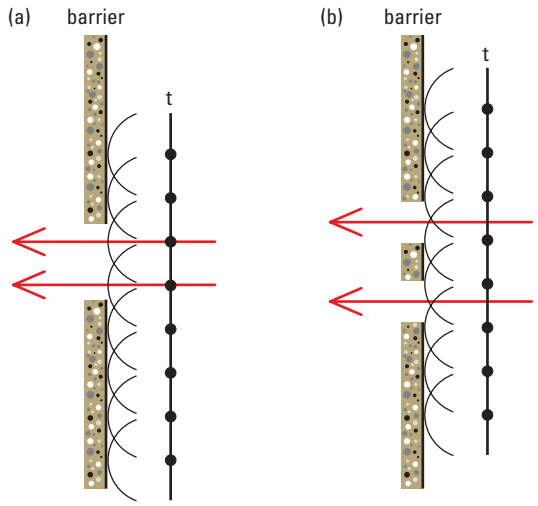
▲ **Figure 13.67** Circular wave front emitted by a light source



▲ **Figure 13.68** Straight wave front emitted by a distant light source

Concept Check

Use Huygens' Principle to predict the wave front shapes that occur after the straight waves pass through the openings shown in Figure 13.69 (a) and (b).



◄ Figure 13.69
At each opening, one or more secondary point sources exist. Draw the line tangent across the wavelets that would exist a short time after the secondary point sources pass through the opening. Explain what has happened to the shape and direction of the wave front after it passed through the barriers in Figure 13.69 (a) and (b).

eSIM
Explore Huygens' Principle through simulations. Follow the eSim links at www.pearsoned.ca/school/physicssource.

According to Huygens' Principle, a periodic straight wave will continue to propagate in a straight line until it encounters a barrier. If the wave front encounters a small opening or aperture in the barrier, the wave front will change shape and direction. This process is called **diffraction**.

diffraction: the change in shape and direction of a wave front as a result of encountering a small opening or aperture in a barrier, or a corner

Young's Experiment

Huygens' wave theory can explain many of the properties of electromagnetic radiation, including reflection and refraction, but initially, the scientific reputation of Newton and his belief in the particle model of light dominated the scientific community. However, in 1801, an experiment by Thomas Young provided significant evidence in support of the wave model of light.

Problems Involved in the Design of the Experiment

In the years leading up to Young's groundbreaking work, scientists studying light were attempting to observe an **interference** pattern that was similar in nature to that of two point sources. They believed that if light were indeed a wave, then two side-by-side light sources should produce an interference pattern similar to that observed with water in a ripple tank (section 8.3). In these early light experiments, the light from the two sources was incident on a nearby screen that was observed for evidence of an interference pattern. What was not well understood at the time was that waves of high frequency and short wavelength result in a very short distance between nodal lines, the regions of destructive interference that appear dark. As we know today, light waves have an extremely high frequency and short wavelength, so the distance between nodal lines would be so small it could

interference: an effect resulting from the passage of two like waves through each other

eSIM
Learn more about Young's classic experiment through simulations. Follow the eSim links at www.pearsoned.ca/school/physicssource.

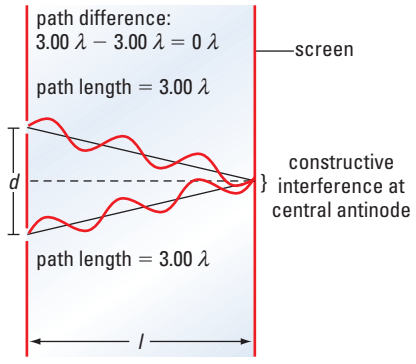
not be observed using traditional means. In addition, to produce an interference pattern, the waves must be in phase. When there are two incandescent lights, each source emits light in random bursts not necessarily in phase with the other source. These bursts of light have a variety of wavelengths that make up all the colours in the spectrum. Therefore, the interference pattern would not be constant, but would vary rapidly over time, making any observation of a pattern more difficult.

The Experiment

Thomas Young solved both of these problems and successfully observed an interference pattern produced by light. Young conducted his experiment using a pinhole in a window shutter and a card he described as "a slip of card, about one-thirtieth of an inch in breadth (thickness)." The card was positioned edgewise into a horizontal sunbeam directed into the room by using a mirror. The sunbeam had a diameter slightly greater than the thickness of the card. When the card was positioned edgewise in the centre of the sunbeam it split the sunbeam into two coherent beams separated by a very small distance (Figure 13.70(a)). The effect was equivalent to light passing through two slits that were very close together. The small distance of separation between the two beams of light expanded the interference pattern on the screen so that the distance between nodal lines was large enough that it could be observed. Light coming from both sides of the card was in phase and the wave fronts could create a fixed interference pattern of light and dark bands, called **interference fringes,** on the screen (Figure 13.70 and also Figure 13.9, page 640). **Bright fringes** or **antinodal lines** were regions of constructive interference and **dark fringes** or **nodal lines** were regions of destructive interference. Young's double-slit experiment provided the strong evidence needed for acceptance of the wave model of light.

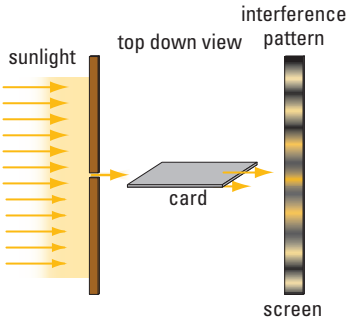
The Interference Pattern

To understand how the interference pattern is created, consider three different points. The first point is the **central antinode** (Figure 13.72). This point occurs at the centre of the pattern, along the perpendicular bisector. The perpendicular bisector is an imaginary straight line that runs from the midpoint of a line joining the two slits to the area of constructive interference on the screen. This area of constructive interference may be called the central antinode, central bright fringe, or central maximum. At the central antinode, both waves travel the same distance from the slits and arrive at the screen in phase. Constructive interference will be observed as a bright band.

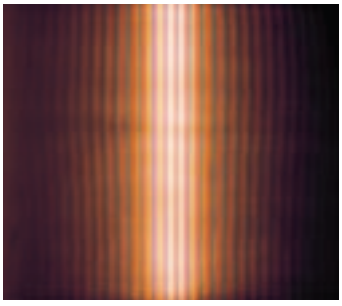


▶ **Figure 13.72** A path difference of zero at the central antinode results in constructive interference and a bright band on the screen.

▼ **Figure 13.70**



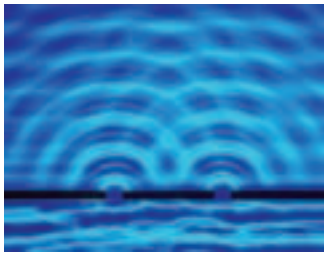
(a) Interference fringes



(b) Photo of two-slit pattern from Young's experiment

info **BIT**

The double-slit experiment works for water waves too! When a single wave front is incident on a barrier with two holes it will produce an interference pattern similar to the one observed by Young. This effect is explored in Unit IV.



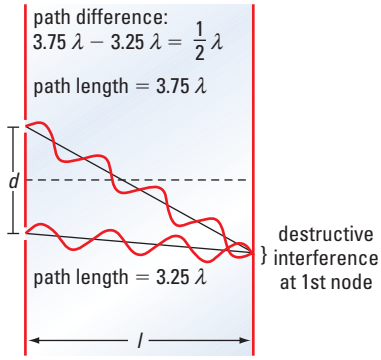
▲ **Figure 13.71** Interference pattern produced by water waves passing through two holes in a barrier

antinode: a point of interaction between waves, at which only constructive interference occurs; in an interference pattern, antinodes occur at path difference intervals of whole wavelengths

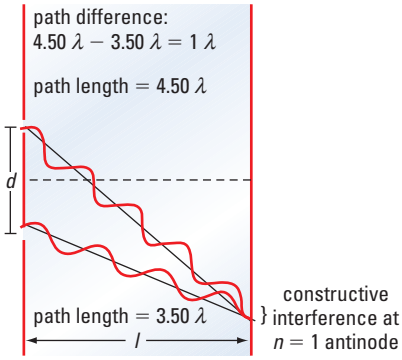
The second point is the first **node,** also called the first dark fringe or the first minimum. At this location, one wave travels a distance of $\frac{1}{2}\lambda$ farther than the other so that the waves arrive out of phase, and destructive interference is observed as a dark band (Figure 13.73).

The third point is another antinode or bright fringe. At this location, one wave travels a distance of 1λ farther than the other, causing the waves to arrive at the screen in phase once again (Figure 13.74). This pattern of bright and dark fringes repeats as we move out in both directions from the central, perpendicular bisector.

node: a point of interaction between waves, at which only destructive interference occurs; in an interference pattern, nodes occur at path difference intervals of one-half wavelength



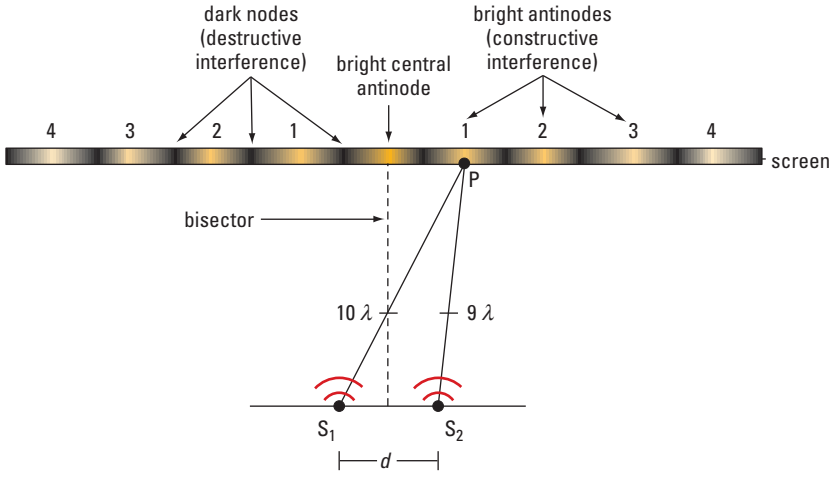
▲ **Figure 13.73** A path difference of $\frac{1}{2}\lambda$, at the first node results in destructive interference and a dark band on the screen.



▲ **Figure 13.74** A path difference of λ, at the first antinode results in constructive interference and a bright band on the screen.

Mathematical Analysis of Young's Experiment

Young's experiment and interference patterns in general contain mathematical information about the waves that create them. For instance, the interference pattern that Young observed can be used to determine the wavelength of the light that created it.



▲ **Figure 13.75** Two point sources, separated by a short distance, produce antinodal lines of constructive interference and nodal lines of destructive interference.

Point sources, S_1 and S_2, from the same original source, are separated by a short distance, d, and produce identical waves that are in phase.

PHYSICS INSIGHT

Compare Figures 13.74 and 13.75. The absolute path lengths (expressed in number of wavelengths) shown in Figure 13.74 and 13.75 are different, yet the waves are still causing constructive interference at the point where they meet. How can this be? If the distance separating the sources and the screen is constant, then the path length (expressed in number of wavelengths) to the antinodes can and will be different for different wavelengths of light. As long as the "difference" in path lengths is a whole number multiple of the wavelength of the light λ, constructive interference will occur where the waves meet and this will be observed as an antinode.

An equal number of antinodal lines, or lines of constructive interference, radiate outward on either side of the perpendicular bisector of the line joining S_1 and S_2. Beginning at the perpendicular bisector, antinodal lines on each side are numbered 1, 2, 3, etc., resulting in a duplicated series (Figure 13.75). For our analysis, we will chose a point, P, on the $n = 1$ antinodal line.

path length: the distance between a point source and a chosen point in space

difference in path length: the difference between two path lengths, each measured from a different origin and extending to a common point in space

The **path length** from S_1 to P and from S_2 to P can be measured in multiples of wavelengths. From Figure 13.75, the path S_1P is 10λ and the path S_2P is 9λ. The **difference in path length** from point P to the two sources is

$$10\lambda - 9\lambda = 1\lambda$$

Therefore, for any point along the first antinodal line (on either side of the bisector), the following relationship is true:

$$S_1P - S_2P = 1\lambda$$

Recall from section 8.3 that waves that are 1λ out of phase will constructively interfere. This explains why the antinodal lines are bright. A similar analysis for a point, P_2, on the $n = 2$ antinodal line generates a similar relationship

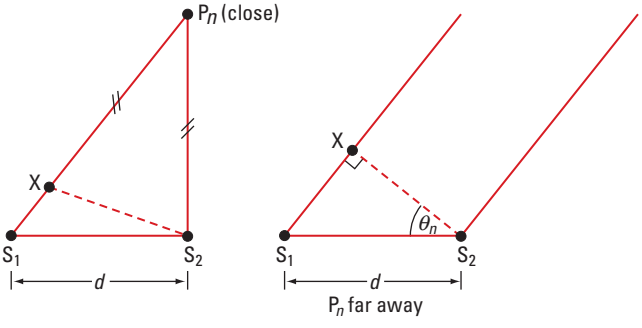
$$S_1P_2 - S_2P_2 = 2\lambda$$

An analysis of points on the $n = 3$ and $n = 4$, etc., antinodal lines follows a similar pattern, generating the following relationship between path difference and wavelength along the antinodal lines.

$$S_1P_n - S_2P_n = n\lambda, \text{ where } n = 1, 2, 3, 4, \ldots \quad (1)$$

If the wavelength is sufficiently large, the difference in path length can be calculated as in Equation (1). Light waves have extremely small wavelengths; therefore, another method of calculating path length becomes appropriate.

Difference in Path Length for Waves of Short Wavelength



▲ **Figure 13.76** Two point sources, separated by a short distance, d, with path lengths to point P_n

Consider the triangles illustrated in Figure 13.76, showing the path length from two sources to point P_n.

For any point along the antinodal line P_n, the difference in path length will be equal to the segment S_1X. When P_n is selected to be very far away, the paths are nearly parallel. In such a case, S_1-X-S_2 forms a right triangle allowing the difference in path length to be expressed in terms of angle θ_n,

$$\sin \theta_n = \frac{S_1X}{d}$$

$$\sin \theta_n = \frac{\textit{difference in path length}}{d}$$

Constructive interference

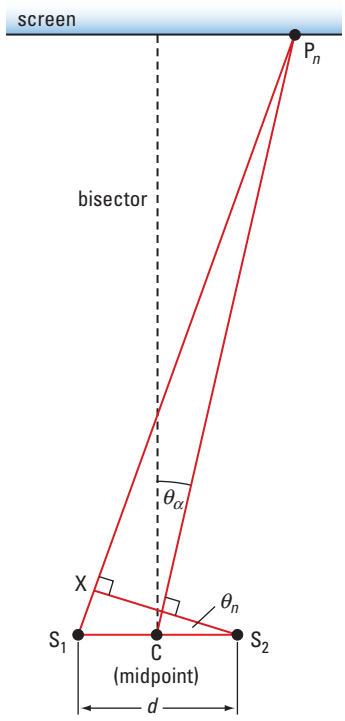
For constructive interference or antinodal lines, substitute the generalization for the difference in path length (Equation 1 above):

$$\sin \theta_n = \frac{n\lambda}{d}$$

$$\lambda = \frac{d \sin \theta_n}{n} \quad \text{for } n = 1, 2, 3, 4, \ldots \text{(2)}$$

Equation (2) can be used to determine the wavelength of the light used to produce the interference pattern, where n is the number of the nth antinodal line and d is the distance between the two sources. For a point P_n located far away from the two point sources, the angle θ_n is equivalent to the angle θ_α, located between the perpendicular bisector and the straight line drawn between the midpoint of the two sources and the point P_n. The angle θ_α is known as the **angle of diffraction** (Figure 13.77).

angle of diffraction: the angle formed between the perpendicular bisector and the straight line to a nodal or antinodal point on the interference pattern



▲ **Figure 13.77** When P_n is far away, line S_1P_n is approximately parallel to CP_n, making θ_n and θ_α equal. θ_α is the angle of diffraction.

Destructive interference

The analysis for destructive interference, which occurs along the nodal lines, is done in an almost identical way. Recall that destructive interference occurs when the path difference between waves is a half number of wavelengths. Therefore, the generalization for the difference in path length becomes

$$\sin \theta_n = \frac{(n - \frac{1}{2})\lambda}{d}$$

$$\lambda = \frac{d \sin \theta_n}{(n - \frac{1}{2})} \quad \text{for } n = 1, 2, 3, 4, \ldots \text{(3)}$$

where n is the number of the nth nodal line relative to the perpendicular bisector, d is the distance between the two sources, and the angle θ_n is equivalent to the angle between the perpendicular bisector and the straight line drawn between the midpoint of the two sources and the point P_n.

Example 13.8

Monochromatic light is incident on two slits separated by 0.30 mm, and the first bright fringe ($n = 1$ antinode) is located at an angle of 0.080° from the central antinode. What is the wavelength of the light?

Given

$d = 3.0 \times 10^{-4}$ m
$\theta_n = 0.080°$
$n = 1$

Required

Wavelength (λ)

Analysis and Solution

The angle given is relative to the central antinode, which occurs along the perpendicular bisector; therefore, the angle given is relative to the perpendicular bisector. The first bright fringe is a region of constructive

Practice Problems

1. Light of an unknown wavelength is incident on two slits separated by 0.20 mm. The second bright fringe is located at an angle of 0.26° from the central antinode. What is the light's wavelength?
2. Blue light of 460 nm is incident on two slits that are 0.55 mm apart. What is the angle of diffraction for the third antinodal line?

3. The second nodal line of an interference pattern occurs at 0.095° relative to the central antinode. The two slits are separated by 0.40 mm. What is the wavelength and colour of light producing this pattern?

Answers

1. 4.5×10^{-7}
2. 0.14°
3. 4.4×10^{-7} m, violet

interference, where the path difference must be one full wavelength different. Therefore, Equation (2) above for constructive interference applies:

$$\lambda = \frac{d \sin \theta_n}{n}$$

$$\lambda = \frac{(30 \times 10^{-4}\ \text{m}) \sin 0.080°}{1}$$

$$\lambda = 4.2 \times 10^{-7}\ \text{m}$$

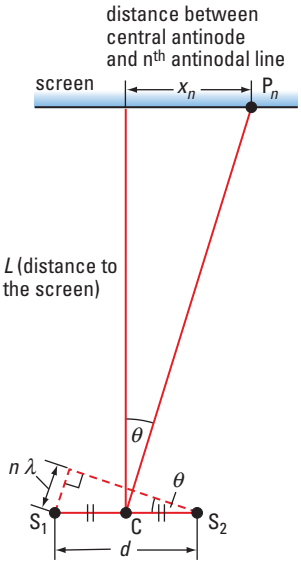
Paraphrase

Monochromatic light with a wavelength of 4.2×10^{-7} m will produce a bright fringe at an angle of 0.080° from the central antinode.

***info* BIT**

When the angle θ is small, sin θ is nearly equal to tan θ as illustrated in the calculated values for both shown below:

Angle θ°	sin θ	tan θ	sin θ/ tan θ
1	0.017452	0.017455	0.9998
2	0.03490	0.03492	0.9994
5	0.08716	0.08749	0.9962
10	0.1736	0.1763	0.9847



▲ **Figure 13.78** Determining sin θ using x and L

Finding Wavelength and the Angle of Diffraction Under Experimental Conditions

In experimental settings, it is often difficult to measure the angle of diffraction because this angle is very small relative to a point that is very far away from the two slits. It is easier to obtain a value for sin θ by determining the ratio x/L, as shown in Figure 13.78. Here, x is the distance between the central antinode (where the perpendicular bisector intersects the screen) and the antinodal fringe. The length of the perpendicular bisector, L, is the distance from the midpoint between the slits to the screen, where the interference pattern is observed.

In Figure 13.78, $x/L = \tan \theta$, but when L is much greater than x, the ratio of x/L is very small (generally less than 0.2) making tan θ nearly equal to sin θ (see Infobit). Therefore, it is acceptable to assume sin $\theta = x/L$ in this case. By replacing sin θ with the ratio x/L, we arrive at the following equation for antinodal (bright) fringes:

$$\lambda = \frac{d\left(\frac{x}{L}\right)}{n}$$

$$\lambda = \frac{xd}{nL}$$

Applying the same analysis to nodal (dark) fringes gives:

$$\lambda = \frac{d\left(\frac{x}{L}\right)}{\left(n - \frac{1}{2}\right)}$$

$$\lambda = \frac{xd}{\left(n - \frac{1}{2}\right)L}$$

Example 13.9

A student measuring the wavelength of light emitted by a krypton gas sample directs the light through two slits separated by 0.264 mm. An interference pattern is created on a screen 3.0 m from the slits and the distance between the second bright ($n = 2$ antinode) fringe and the central antinode is measured to be 1.18 cm. What is one of the wavelengths of light emitted by the krypton gas sample?

Given

$d = 2.64 \times 10^{-4}$ m
$L = 3.0$ m
$x = 1.18 \times 10^{-2}$ m
$n = 2$

Required

wavelength (λ)

Analysis and Solution

The bright fringe is a region of constructive interference, where the path difference must be a whole number of wavelengths. Solve for the wavelength by using the equation:

$$\lambda = \frac{xd}{nL}$$

$$\lambda = \frac{(1.18 \times 10^{-2}\ \cancel{\text{m}})(2.64 \times 10^{-4}\ \text{m})}{(2)(3.0\ \cancel{\text{m}})}$$

$$\lambda = 5.2 \times 10^{-7}\ \text{m}$$

Paraphrase

The krypton gas sample emits light with a wavelength of 5.2×10^{-7} m.

Practice Problems

1. Monochromatic light is incident on two slits separated by 0.15 mm. An interference pattern is observed on a screen 5.0 m away. The distance between the 3rd dark fringe and the central antinode is 4.50×10^{-2} m. What is the wavelength of the light?
2. Monochromatic light is incident on two slits separated by 3.00×10^{-5} m. The distance between antinodes is 3.10×10^{-2} m. If the screen is 1.50 m from the slits, what is the light's colour and wavelength ?
3. A student used light of wavelength 5.00×10^{-7} m and found that the distance between the third node and the central antinode was 1.00×10^{-1} m. If the screen was located 1.20 m away from the slits, how far apart are the slits?

Answers

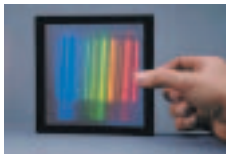
1. 5.4×10^{-7} m
2. 6.20×10^{-7} m, red
3. 1.50×10^{-5} m

Poisson's Bright Spot

Using an analysis similar to that in Example 13.9, Young calculated the wavelength of various colours of light and announced his results in 1807. He was still overshadowed by Newton's reputation and support for the particle model of light. Thus, Young was not taken seriously by the scientific community until 1818, when Augustin Fresnel, a French physicist (Figure 13.79), proposed another mathematical wave theory. This new theory formed a critical turning point in the debate between the wave and particle models of the time. A mathematician by the name of Simon Poisson argued that the equations in Fresnel's theory could be used to predict a unique diffraction pattern that should be produced when light is incident on a small round disc. Poisson showed that Fresnel's equations should produce a central bright fringe at the centre of a shadow cast by a solid round disc when it is illuminated by a point source of monochromatic light (Figure13.80(a)). This predicted result was similar to the central bright fringe observed in Young's double-slit experiment.

▲ **Figure 13.79** Augustin Fresnel (1788–1827). Fresnel's analysis of diffraction provided the theoretical groundwork for the transverse wave model of light. He also designed the lenses that were used in lighthouses of the 19th century and in overhead projectors, solar collectors, and beacon lights of the 21st century.

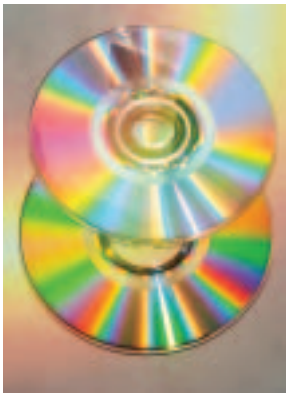
diffraction grating: a sheet of glass or plastic etched with a large number of parallel lines. When light is incident on the grating, each line or slit acts as one individual light source.



▲ **Figure 13.81** Diffraction grating

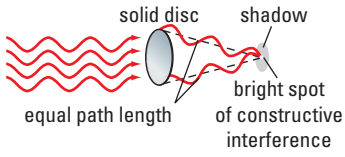
info **BIT**

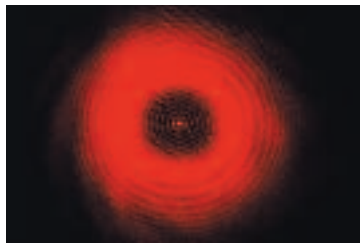
The concentric circles cut into a CD when it is made make it behave as a diffraction grating. So, the rainbow pattern you see when you look at a CD is the product of interference caused by diffraction.



▲ **Figure 13.82**

Fresnel's equations showed that the light that is diffracted around the edge of the disc should constructively interfere at the centre of the shadow. Poisson was unable to observe this bright spot experimentally and was of the opinion that he had refuted the wave model of light.





▲ **Figure 13.80** Poisson's Bright Spot
(a) Constructive interference at the bright spot (b) Photograph of Poisson's Bright Spot

Poisson's prediction of a bright spot was retested by Dominique Arago in 1818, and this time, the bright spot was verified (Figure 13.80 (b)). The bright spot is known as "Poissson's Bright Spot" because, even though Poisson was a supporter of the particle model of light, he had predicted the spot's existence if the wave model of light was correct. Mainly as a result of this verification of Poisson's Bright Spot, by 1850 the wave model of light was generally accepted by the scientific community. The model was then successfully applied to many of the properties of light.

Diffraction Gratings

Young's experiment used only two small point sources of light that were in phase. A **diffraction grating** (Figure 13.81) has a very large number of equally spaced, parallel lines that act as individual light sources. When light is incident on a multi-slit diffraction grating, an interference pattern, similar to that of a double slit, is produced on a distant screen. But there are several key differences. First, the large number of lines in a diffraction grating can deliver more light energy to the distant screen, increasing the brightness of the interference pattern. Second, the antinodal, bright fringes are more defined, being sharper and narrower. And third, when line separation is very small, the separation between the lines (d) is inversely proportional to the distance between the fringes (x) in the interference pattern according to

$$\lambda = \frac{xd}{nL}$$

$$d = \frac{\lambda nl}{x}$$

Therefore, the extremely small separation distance between lines on a grating will cause an increase in the separation between the fringes in the pattern. For these reasons, a diffraction grating is a very precise apparatus for investigating the wavelength of light.

When a diffraction grating is used with monochromatic light, the interference pattern will have the same colour as the wavelength of light used to produce it. When full-spectrum, white light is used, each antinode will appear as a rainbow because each wavelength is diffracted

at a slightly different angle. The relationship between the wavelength and the angle is:

$$\sin \theta_n = \frac{n\lambda}{d}$$

as was derived earlier for Young's double-slit experiment.

Diffraction gratings are produced by etching a large number of parallel lines on a sheet of glass or plastic. Each grating is defined by the number of lines per centimetre etched on it. Tens of thousands of lines per centimetre are common. The distance between lines is the inverse of the number of lines per centimetre, so as the number of lines increases, the distance between any two lines decreases accordingly.

eLAB

For a probeware activity, go to www.pearsoned.ca/school/physicssource.

eSIM

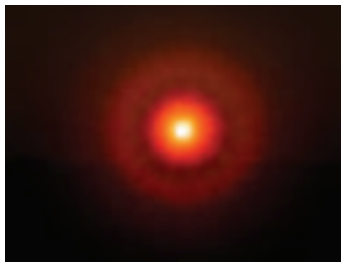
Investigate diffraction gratings through the use of simulations. Follow the eSim links at www.pearsoned.ca/school/physicssource.

eWEB

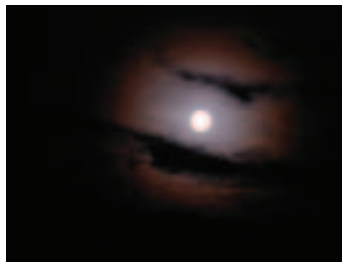
To learn more about diffraction effects in nature, follow the links at www.pearsoned.ca/school/physicssource.

Diffraction in Nature — Solar and Lunar Coronas

When the Sun is rising (Figure 13.83) or an overexposed photo of the Moon is taken (Figure 13.84), a pattern of rings appears. These are examples of diffraction in the atmosphere. When light from the Sun or Moon enters the atmosphere it encounters uniformly sized droplets of water and ice crystals. Diffraction occurs as the light bends around the edges of the particles at varying degrees depending upon the wavelength of the light. A series of coloured rings surrounding the astronomical object results.



▲ **Figure 13.83** A rising Sun



▲ **Figure 13.84** A ring around the Moon

Example 13.10

A diffraction grating has 1000 lines/1 cm. When light passes through the grating, an interference pattern is produced on a screen 4.00 m away. The first-order bright fringe is 19.2 cm away from the central antinode. What is the wavelength and colour of the light?

Given

$d = 1 \text{ cm} / 1000 \text{ lines} = 1.000 \times 10^{-3} \text{ cm/line}$
$= 1.000 \times 10^{-5} \text{ m/line}$
$x = 1.92 \times 10^{-1} \text{ m}$
$n = 1$
$L = 4.00 \text{ m}$

Required

wavelength of light (λ)

Analysis and Solution

The separation between lines is the inverse of the lines per centimetre given for the diffraction grating. Line separation is very small, and the first-order bright fringe is $n = 1$ because it is an antinode, or line of constructive interference. Therefore, this equation applies:

Practice Problems

1. An unknown wavelength of light is incident on a diffraction grating with 2500 lines/cm. The distance between the central antinode and the 3rd dark node is 20.0 cm when the screen is located 50.0 cm from the grating. Determine the wavelength of the light.
2. How many lines/cm are there in a diffraction grating if the 3rd dark fringe is located 5.00 cm from the central antinode when the screen is located 60 cm from the grating? Assume $\lambda = 500$ nm.
3. A diffraction grating has 1000 lines/cm. When red light ($\lambda = 750$ nm) is incident on the grating, what will be the separation between bright antinodes on a screen 3.0 m away?

Answers

1. 6.40×10^{-7} m
2. 6.7×10^{2} lines/cm
3. 23 cm

$$\lambda = \frac{xd}{nL}$$

$$\lambda = \frac{(1.92 \times 10^{-1}\ \text{m})(1.000 \times 10^{-5}\ \text{m})}{(1)(4.00\ \text{m})}$$

$$\lambda = 4.80 \times 10^{-7}\ \text{m}$$

$$\lambda = 480\ \text{nm}$$

Paraphrase

Based on the interference pattern, the incident light is 480 nm, which corresponds to the colour blue.

13-10 Inquiry Lab

Required Skills

- Initiating and Planning
- Performing and Recording
- Analyzing and Interpreting
- Communication and Teamwork

Determining the Wavelength of Red, Green, and Blue Light

This investigation will verify the known wavelengths of different colours of light. According to the visible spectrum, red, green, and blue light have wavelengths in the following ranges:

- red: 650–750 nm
- green: 500–550 nm
- blue: 450–500 nm

Question

What are the wavelengths of red, green, and blue light?

Variables

manipulated: the distance between the diffraction grating and the screen will be indirectly manipulated
responding: the position of the first-order antinodes for red, blue, and green light on the "apparent" screen
controlled: single-filament incandescent light source and diffraction grating

Materials and Equipment

thin-film diffraction grating
two metre-sticks
single-filament lamp
masking tape and pen

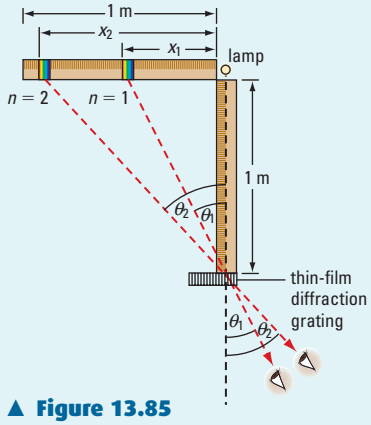
Experimental Design

To investigate the position of the first- and second-order antinodes in an interference pattern produced by white light, a "simulated" screen will be used. Two metre-sticks and a lamp are arranged as shown in Figure 13.85.

In this design, observers look through the diffraction grating to see the antinodes as they would appear on a screen behind them. A screen is not needed as the angles θ are identical, so we can assume the distance to the hypothetical screen is identical to the distance between the lamp and the grating (1.0 m). While one person observes the antinode, a second person is directed to place an identification tape on the metre-stick where the antinode appears to be. This allows the distance between the central antinode and the position of the first-order antinode to be measured. This procedure can also be used to find the position of the second-order antinode.

Procedure

1. Set up the two metre-sticks such that they make a right angle with one another.
2. Place the lamp at the point where the metre-sticks join as shown in Figure 13.85.
3. Place the thin-film diffraction grating vertically upright at the end of one of the metre-sticks.



▲ **Figure 13.85**

4. Turn on the lamp and look through the grating, moving your head side to side until you can see the first-order antinode, which should appear as a rainbow. Your eye acts as the wavelength detector, in place of a screen.
5. While looking at the antinode, direct your lab partner to put a piece of tape labelled "B" on the metre-stick where the blue antinode band appears to be.
6. Repeat step 5 using tape labelled "G" for the green band of light and "R" for the red band of light.
7. Repeat steps 5 and 6 for the second-order antinode, if it is visible along the metre-stick.
8. Record the distance between the lamp and each piece of labelled tape.

Analysis

1. Using the first antinode ($n = 1$), calculate the wavelength of red, blue, and green light.
2. Determine the mean wavelength of each colour of light using the ranges given.
3. Calculate the percent difference between the mean wavelength of each colour and your experimentally determined value.
4. Explain why each antinode appears as a rainbow. Hint: What effect does the wavelength have on the angle of diffraction?
5. How many antinodes should appear in the diffraction grating on either side of the light source? Assume the largest angle of diffraction that could be visible is 89°.

MINDS ON Comparing Spectra: Dispersion vs. Diffraction

The rainbow produced when white light is refracted through a prism is similar to the rainbow produced at each antinode when white light passes through a thin-film diffraction grating.

In small groups, prepare a presentation to compare and contrast these two phenomena. Your presentation should consider:

1. The wave nature of light
2. The similarities of refraction and diffraction as they relate to Huygens' Principle of wavelets
3. The different wavelengths of the visible spectrum and how this leads to the separation of the colours in both dispersion and diffraction
4. The key differences in the causes of dispersion in a prism and the production of antinodes in an interference pattern
5. The reversed order of colours

Your presentation should also include:

- relevant images of both phenomena
- schematics of each phenomenon using ray diagrams where appropriate
- the use of animations and simulations found at www.pearsoned.ca/school/ physicssource
- a list of references

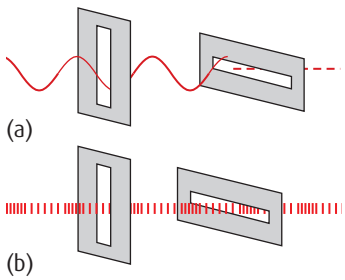
eLAB

For a probeware activity, go to www.pearsoned.ca/school/physicssource.

Polarization

Young's double-slit experiment, and interference in general, provided strong evidence that light does exhibit wave properties. However, evidence of interference alone could not distinguish whether the waves were transverse or longitudinal. Recall that in section 13.1 light, and electromagnetic radiation in general, was described by Maxwell as consisting of perpendicular electric and magnetic fields, propagating through space at the speed of light. In other words, Maxwell predicted that light was a transverse wave. Is there evidence that this is indeed the case?

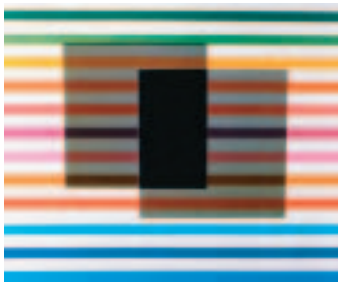
Using a mechanical model, such as a rope, one can see that a transverse wave can be linearly polarized when vibrations only occur in one plane. The vertically polarized transverse waves shown in Figure 13.86 can pass through the vertical slit, but are blocked, or absorbed, by the horizontal slit. The longitudinal waves, on the other hand, can pass



▲ **Figure 13.86** (a) A transverse wave passing through a vertical slit and being absorbed by a horizontal slit (b) A longitudinal wave passing through both a vertical and a horizontal slit

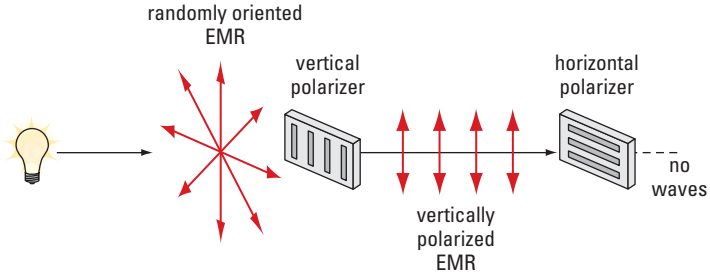
through both slits unaffected because longitudinal waves are not linearly polarized.

By a process similar to the mechanical model, electromagnetic waves can be blocked by two **polarizing filters** held at right angles to one another. In 13-1 QuickLab at the beginning of the chapter, you discovered that two polarizing filters, held at right angles to one another, can absorb light.



◀ **Figure 13.88** Two polarizing filters, one held vertically, the other held horizontally, partially overlap, showing the absorption of electromagnetic waves.

The photograph in Figure 13.88 can be explained by considering electromagnetic radiation as perpendicular magnetic and electric fields, with the plane of **polarization** arbitrarily defined by the direction of the electric field. When light is produced by an incandescent light bulb it is not polarized, meaning that the plane of the electric fields for each wave occurs randomly as light propagates outward from the source in all directions. When unpolarized light is incident on a polarizing filter, only one plane of the electric field is allowed to pass through, causing **plane polarized light** to emerge. If a second polarizing filter is held at right angles to the plane polarized light, then the plane polarized light also is absorbed (Figure 13.89).



▲ **Figure 13.89** Unpolarized light incident on two polarizing filters at right angles to one another

The blue light in sunlight is partially polarized when it is scattered in the atmosphere. Therefore, in sunglasses and camera lenses, polarized filters are used to reduce the blue polarized light from the sky while allowing other non-polarized colours to pass through and appear brighter. To see this effect, tilt your head from side to side while looking at the blue sky with polarized glasses.

The polarizing effect supports the wave model of light in general and in particular, the concept that light is composed of perpendicular, oscillating electric and magnetic fields (Figure 13.90).

***info* BIT**

Ancient Inuit hunters developed a unique technology to limit the glare of the Sun's light reflecting off the spring snow. Snow goggles, similar to those seen in the movie *Atanarjuat: The Fast Runner,* were the first sunglasses. The goggles were carved mainly from caribou antler whalebone, or ivory; driftwood was also used. Narrow slits in the snow goggles reduced the amount of light, thus protecting the hunter's eyes and preventing the debilitating effects of snow blindness. A secondary positive effect of the goggles was improved visibility.

▲ **Figure 13.87**
Inuit snow goggles

polarizing filter: a filter that allows only one plane of the electric field to pass through it; plane polarized EMR emerges

polarization: production of a state in which the plane of the electric field for each electromagnetic wave occurs only in one direction

plane polarized light: light resulting from polarization, in which only one plane of the electric field is allowed to pass through a filter

▲ **Figure 13.90** Two pairs of polarized sunglasses, at right angles

13.5 Check and Reflect

Knowledge

1. According to Huygens' Principle, what will happen to the shape of a straight wave front after it passes through a small opening in a barrier?
2. Use Huygens' Principle to describe how interference can occur when a straight wave front is incident on two narrow openings.
3. Two incandescent white lights are placed close to one another. Explain why an interference pattern is not observed on a nearby screen.
4. What parameters did Young need to control to enable him to observe an interference pattern from two point sources of light?
5. Construct a concept map to show the relationship between path length, nodal fringes, antinodal fringes, wave phase, and interference.

Applications

6. In an experiment similar to Young's, how far apart are two slits if the 3rd antinode is measured to be 20° from the central antinode, when light with a wavelength of 650 nm is used?
7. Determine the angle of diffraction to the 2nd node when light with a wavelength of 425 nm is incident on two slits separated by 6.00×10^{-6} m.
8. Light with a wavelength of 700 nm is diffracted by a diffraction grating with 5.00×10^{3} lines/cm. If a screen is positioned 1.00 m away from the grating, what is the distance between the 1st and central antinodes?
9. Monochromatic light with a frequency of 5.75×10^{14} Hz is incident on a diffraction grating with 60 lines/cm. What is the distance between the 2nd and 3rd dark fringes when the screen is located 1.20 m away?
10. An unknown light source is directed at a diffraction grating with 6.00×10^{4} lines/m. If the nodal lines are 5.50 cm apart when the screen is 1.50 m away, what is the wavelength and frequency of the light?
11. Light emitted from an unknown gas sample is incident on a diffraction grating with 5.00×10^{2} lines/cm. The antinodes appear on a screen 1.50 m away and are separated by 3.10×10^{-2} m. What is the wavelength and frequency of the light?

Extensions

12. Design an experiment to determine the wavelength of an unknown monochromatic light. Include an experimental design, material list, and procedure.
13. Compare the wavelength of X rays to that of visible light and explain what should happen to the diffraction pattern if X rays were used instead of visible light.
14. Investigate how the process of diffraction, using radiation other than visible light, can be useful for determining the shapes of crystal lattices and structures too small to be seen with visible light.

eTEST

To check your understanding of diffraction, interference, and polarization, follow the eTest links at www.pearsoned.ca/school/physicssource.

Key Terms and Concepts

electromagnetic radiation
frequency
wavelength
electromagnetic spectrum
particle model
wave model
photon
quantum model
electric field
magnetic field
capacitor
Maxwell's Equations
electromagnetic wave
rectilinear propagation
ray diagram
plane mirror
law of reflection
virtual image
real image
magnification
image attitude
converging mirror
diverging mirror
mirror equation
refraction
refractive index
Snell's Law
total internal reflection
critical angle
spectrum
dispersion
converging lens
diverging lens
thin lens equation
Huygens' Principle
diffraction
interference
antinode
node
path length
difference in path length
angle of diffraction
diffraction grating
polarizing filter
polarization
plane polarized light

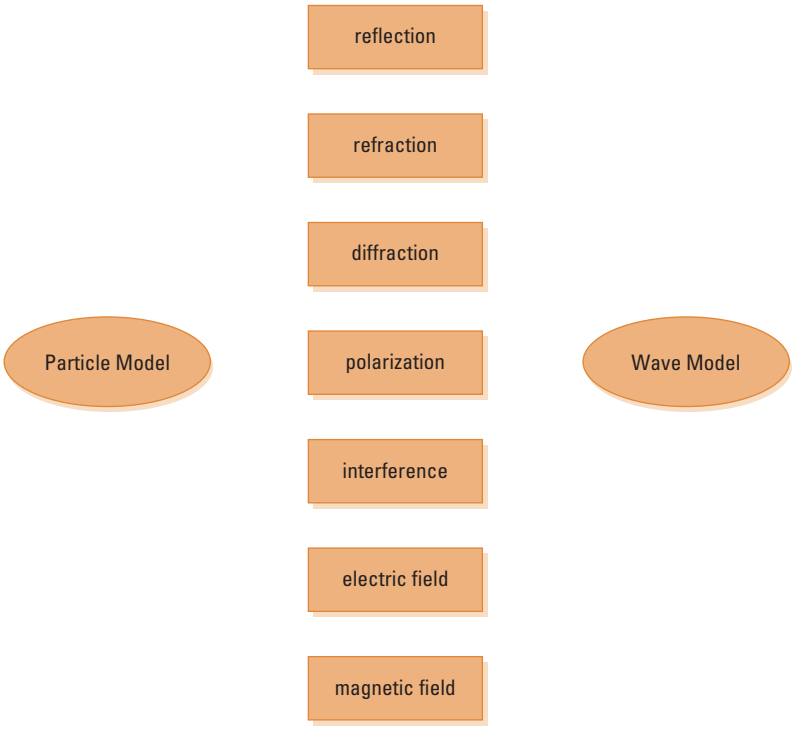
Key Equations

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \qquad \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \qquad n = \frac{c}{v} \qquad n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1} \qquad \sin\theta_n = \frac{n\lambda}{d} \qquad \lambda = \frac{xd}{nL}$$

Conceptual Overview

Summarize this chapter by explaining how the properties of electromagnetic radiation support either the wave model of light or the particle model of light, or both.



Knowledge

1. (13.1) Create a table to identify all the major categories of electromagnetic radiation, including the wavelengths and frequencies listed in the spectrum shown in Figure 13.4. Brainstorm common uses for each type of radiation.
2. (13.1) Compare and contrast the particle and wave models of electromagnetic radiation.
3. (13.1) What two critical insights were understood by Maxwell when he developed his theory of electromagnetic radiation?
4. (13.1) Consider two electric field lines on a transverse wave. One field line is up, and a moment later, another is down. What is produced as a result of this "changing" electric field?
5. (13.1) Describe how an electromagnetic wave is able to propagate in empty space.
6. (13.1) Describe the five predictions that Maxwell made regarding the properties of electromagnetic radiation.
7. (13.1) How did Hertz prove that the EMR observed at his antenna was, in fact, produced by the nearby spark gap and did not originate from another source?
8. (13.2) The first significant attempt to measure the speed of light was made by Christiaan Huygens, using the eclipse of Jupiter's moon Io. Describe this method.
9. (13.2) In addition to measuring the speed of light with a rotating toothed wheel, Armand Fizeau demonstrated that light travelled at different speeds in moving water. Explain how the results of his investigation support the wave model of light.
10. (13.3) Draw a ray diagram to demonstrate the law of reflection.
11. (13.3) Construct a ray diagram for a converging mirror and illustrate the following terms.
    (a) centre of curvature (C)
    (b) radius of curvature (r)
    (c) vertex (V)
    (d) principal axis (PA)
    (e) principal focal point (F)
    (f) focal length (f)
12. (13.3) Can a diverging mirror produce a real image? Explain.
13. (13.4) Using a ray diagram, illustrate partial reflection and partial refraction for a ray passing from air into water at an angle of 15°. On your ray diagram, label the normal line, the index of refraction, the angle of incidence, the angle of reflection, and the angle of refraction.
14. (13.4) Light passes from a medium with a high refractive index to one with a low refractive index. Is the light bent away from or toward the normal line?
15. (13.4) Contrast the simple and general forms of Snell's Law.
16. (13.4) Dispersion is the separation of white light into all the colours of the spectrum. Explain two different methods that could be used to separate all the colours in white light.
17. (13.5) Illustrate the process of refraction using a straight wave front that travels from air into water. Based on your diagram, does Huygens' Principle support the wave model or the particle model of light?
18. (13.5) A straight wave front is incident on two small holes in a barrier; illustrate the shape of the wave front a moment after it makes contact with the barrier. Does your drawing indicate that interference will occur?
19. (13.5) Why is an interference pattern not observed when two incandescent lights are located next to one another?
20. (13.5) How does the evidence from polarizing filters support the transverse nature of the wave model of light?
21. (13.5) Each antinode appears as a full spectrum when white light is incident on a diffraction grating. Explain this phenomenon.
22. (13.5) Explain how path length and diffraction are related to the production of Poisson's bright spot.

Applications

23. (13.1) High-voltage transmission lines that carry alternating current can interfere with radio waves. Explain how this interference can occur.

24. (13.2) Calculate the speed of yellow light, $\lambda = 589$ nm, in the following materials:
(a) water
(b) ethanol
(c) Lucite®
(d) quartz glass
(e) diamond

25. (13.2) An 8-sided mirror is rotating at 5.50×10^2 Hz. At what distance should the fixed mirror be placed to replicate Michelson's experiment?

26. (13.2) A fixed mirror and a rotating mirror are separated by 30.0 km. The 8-sided rotating set of mirrors turns at 600 Hz when the light is able to pass through the experimental apparatus. Calculate the speed of light.

27. (13.3) When you look into a plane mirror, an image is formed. Describe the characteristics of the image based on attitude, type, and magnification.

28. (13.3) A student stands 30 cm from a plane mirror. If the student's face is 25 cm in length, what is the minimum length of mirror needed for the student to see her entire face?

29. (13.3) An object is located 25.0 cm from a converging mirror with a focal length of 15.0 cm. Draw a scale ray diagram to determine the following:
(a) the image location and type
(b) the image attitude
(c) the magnification of the image

30. (13.3) Construct a ray diagram for a diverging mirror and illustrate the following terms:
(a) centre of curvature (C)
(b) radius of curvature (r)
(c) vertex (V)

31. (13.3) Where must an object be placed relative to the focal point for a converging mirror such that the image produced is virtual?

32. (13.3) A 15.0-cm-high object is placed 20.0 cm from a diverging mirror with a virtual focal length of 10.0 cm. How high is the image and where is it located?

33. (13.3) A 20.0-cm-high, inverted image is produced when an object is placed 12.0 cm from a converging lens with a focal length of 11.0 cm. Calculate the height of the object.

34. (13.4) Light with a wavelength of 610 nm is incident on a quartz glass crystal at an angle of 35°. Determine the angle of refraction and the wavelength of the light in the quartz glass.

35. (13.4) Can total internal reflection occur when light travels from
(a) air into water?
(b) water into air?
(c) Lucite® into water?
(d) water into diamond?

36. (13.4) Light enters an unknown material and slows down to a speed of 2.67×10^8 m/s. What is the refractive index of the unknown material? Compare the refractive index of this material to that of water — which one has a higher index?

37. (13.4) Calculate the critical angle of the following boundaries:
(a) water-air
(b) diamond-air
(c) diamond-water
(d) Lucite®-air

38. (13.4) Use a ray diagram to determine the image attributes when the object is located between
(a) 2F′ and F′ for a converging lens
(b) F′ and a converging lens
(c) F′ and a diverging lens

39. (13.4) A 4.00-cm-high object is located 5.00 cm from a diverging lens with a focal length of 10.0 cm. Using the thin lens equation, determine the image attributes and position. Verify your answer with a scale ray diagram.

40. (13.5) In an experiment similar to Young's, light with a wavelength of 630 nm is incident on two slits separated by 5.3×10^{-5} m. What is the angle to the 1st, 2nd, and 3rd antinodes?

41. (13.5) Monochromatic light is incident on two slits separated by 0.25 mm. The first dark fringe deviated an angle of 0.050° from the central antinode. What is the wavelength and colour of the light?

42. (13.5) Light from an unknown gas sample is incident on two slits separated by 1.4×10^{-4} m. On a screen 1.1 m away, the distance between the 7th node and the central antinode is measured to be 0.025 m. What is the wavelength of the light emitted by the unknown gas sample?

43. (13.5) A screen is located 4.5 m from two slits that are illuminated with a 490-nm light source. If the distance between the central antinode and the first-order antinode is 0.037 m, how far apart are the two slits?

Extensions

44. An X-ray machine operates by accelerating an electron through a large potential difference, generating a large amount of kinetic energy. The high-speed electron then collides with a metal barrier. Explain why the collision produces a high-frequency X ray.

45. Cable television wires have a metal shield surrounding the copper wire that carries the television signal. The shielding prevents interference from electromagnetic radiation and it must be grounded in order to effectively block interference. Explain how the shielding prevents interference and why it needs to be grounded.

46. Handheld two-way radios can communicate over relatively short distances. Suggest several ways to increase the radio's range.

47. When you place the concave side of a spoon on your nose and slowly pull it away from your face, your image disappears at a certain distance. What is the significance of this distance?

48. After light enters Earth's atmosphere it encounters a temperature gradient as it approaches the surface of Earth, causing a mirage. If the warm air near the surface of Earth has a lower index of refraction than the cooler air above, which way is the light bent? Show this with a ray diagram.

49. Explain why a fibre-optic network is much more efficient and powerful than a copper-wire network.

Consolidate Your Understanding

1. Explain how electromagnetic radiation is able to propagate in the absence of a medium, like air. Does your explanation support the wave model or particle model?

2. Why is an accelerating charge required to produce electromagnetic radiation and how does this relate to the word "changing" in Maxwell's explanation of EMR?

3. Is an electromagnetic wave one-dimensional, two-dimensional, or three-dimensional? Explain.

4. Has Maxwell's last prediction been verified by experimental evidence? If so, describe the evidence as it relates to reflection, refraction, diffraction, interference, and polarization.

5. Could Hertz have investigated the phenomenon of diffraction by using the same equipment as in his famous experiment? If so, how?

Think About It

Review your answers to the Think About It questions on page 635. How would you answer each question now?

*e*TEST

To check your understanding of the nature and behaviour of electromagnetic radiation, follow the eTest links at www.pearsoned.ca/school/physicssource.